Transparency of a 100ℓ liquid xenon scintillation calorimeter prototype and measurement of its energy resolution for 55 MeV photons

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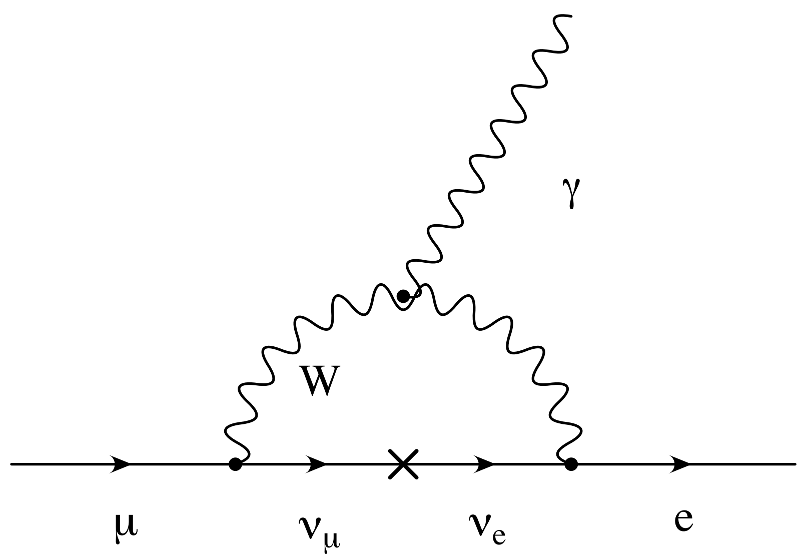
for the MEG collaboration
http://meg.psi.ch

The μ→eγ decay

- MEG collaboration: Italy/Japan/Russia/Switzerland, experiment to be performed at Paul Scherrer Institut (Zurich)
- The μ→eγ decay is forbidden in the Standard Model of elementary particles because of the (accidental) conservation of lepton family numbers
- The introduction of neutrino masses and mixings induces μ→eγ radiatively, but at a negligible level

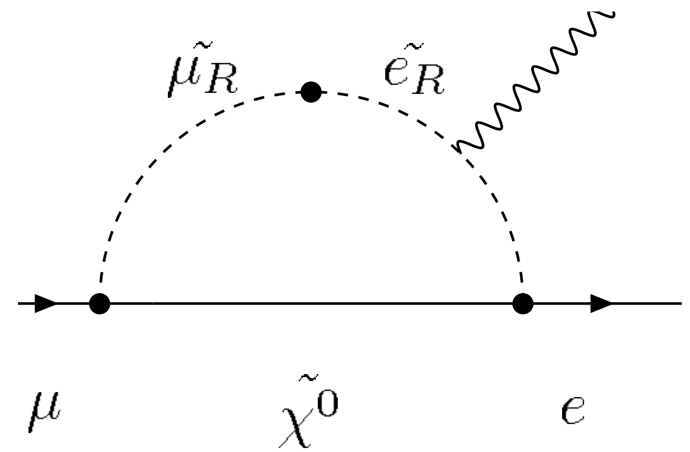


$$\Gamma(\mu \to e\gamma) \approx \frac{G_F^2 m_\mu^2}{192\pi^3}\left(\frac{\alpha}{2\pi}\right)\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)$$

Relative probability ~ 10^{-55}

- All SM extensions enhance the rate through mixing in the high energy sector of the theory

For instance... predictions



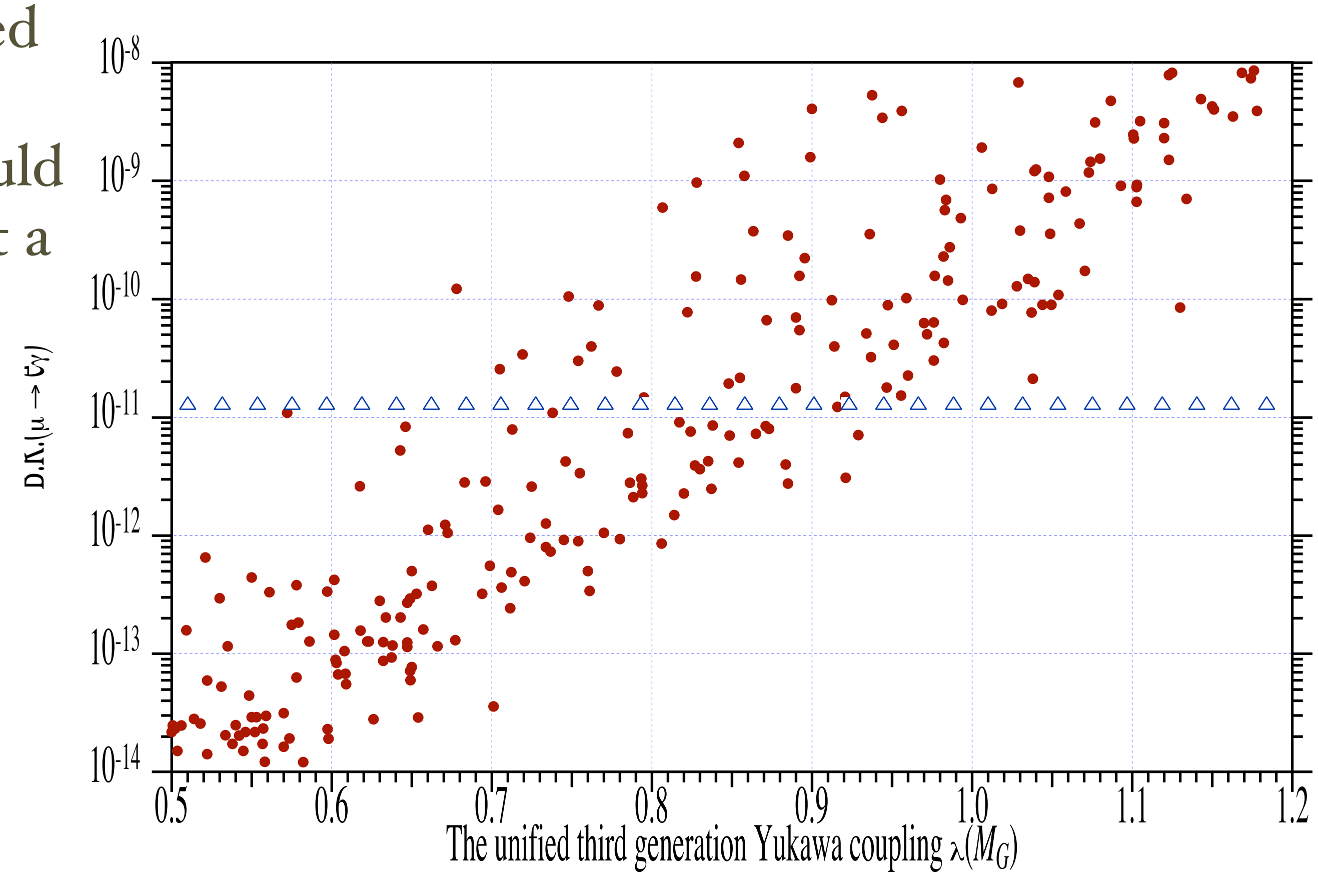
R. Barbieri et al.,Nucl. Phys. B445(1995) 215

J.Hisano et al.,Phys. Lett. B391 (1997) 341

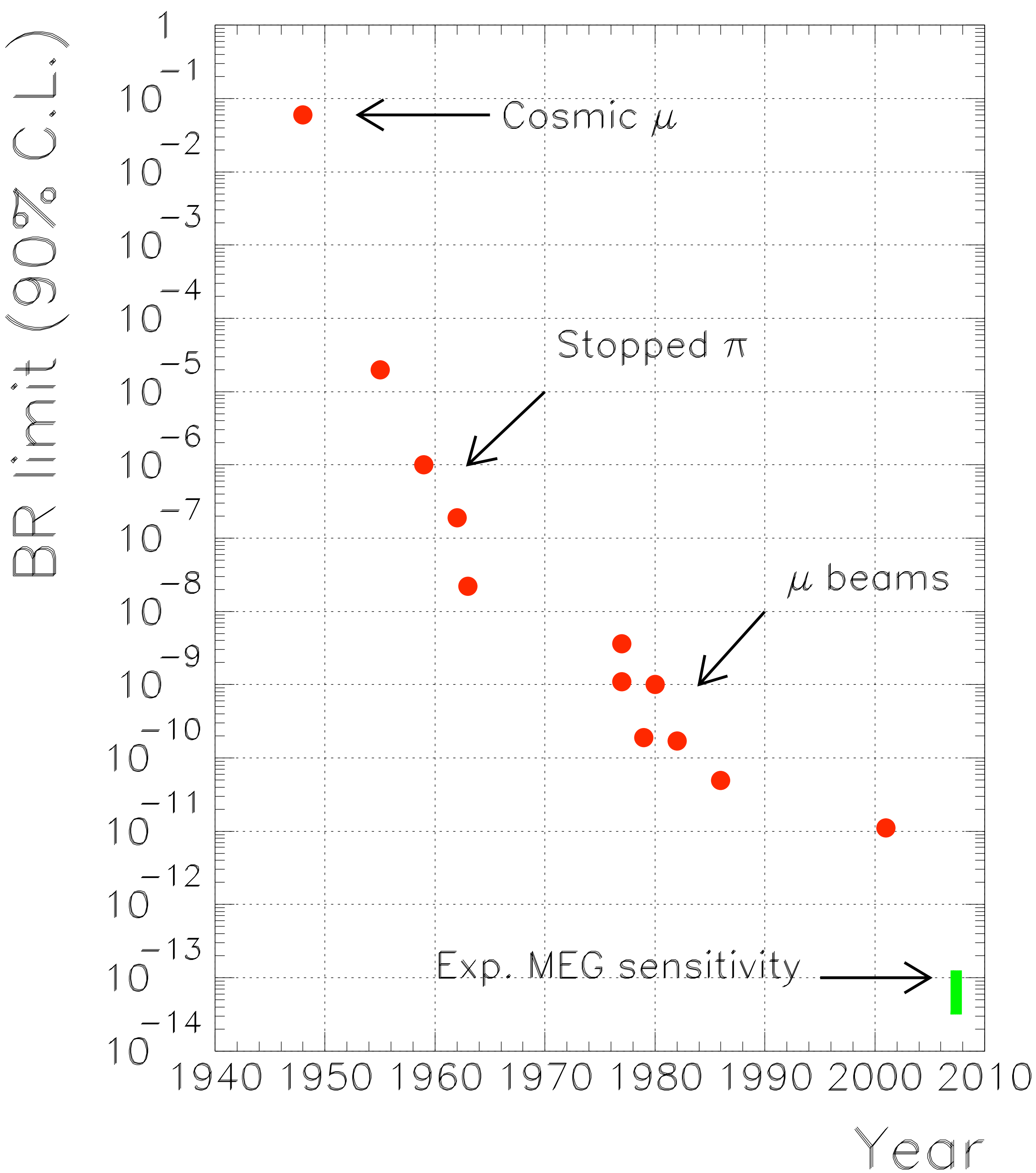
P. Ciafaloni, A. Romanino, A. Strumia, Nucl. Phys. B458 (1996)

J. Hisano, N. Nomura, Phys. Rev. D59 (1999)

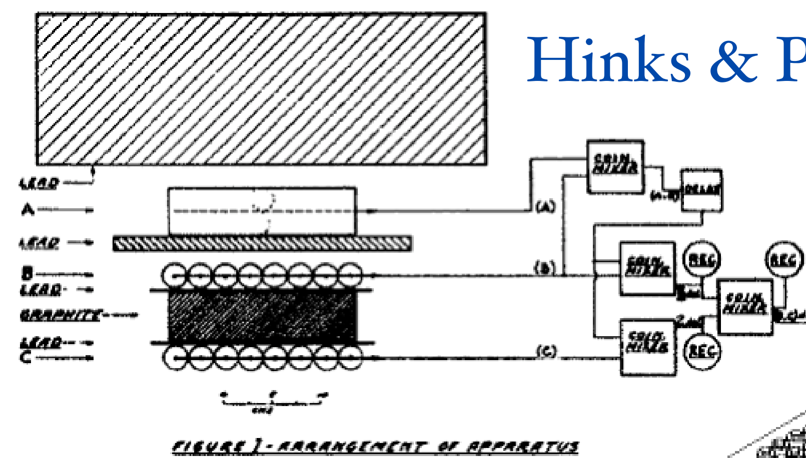
- SUSY SU(5) predictions: LFV induced by finite slepton mixing through radiative corrections. The mixing could be large due to the top-quark mass at a level of 10^{-12} 10^{-15}
- SO(10) predicts even larger BR:
  - m(τ)/m(μ) enhancement
- Models with right-handed neutrinos also predict large BR
- ⇒ clear evidence for physics beyond the SM.



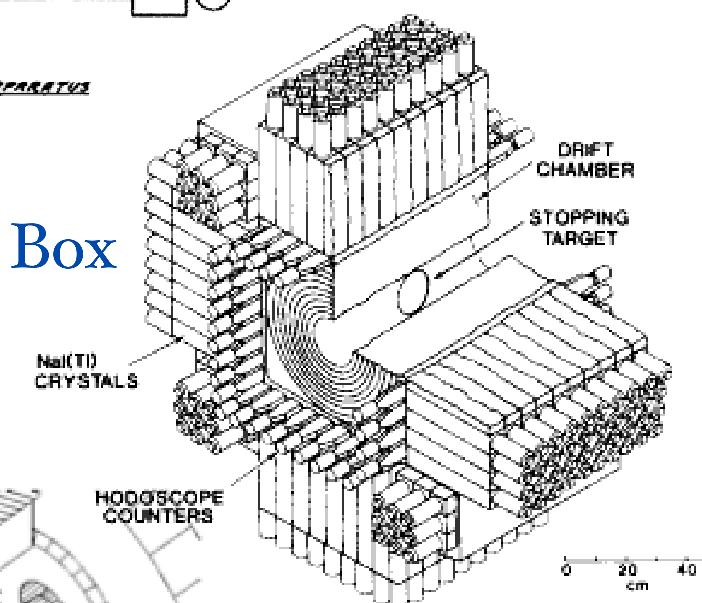
Historical perspective

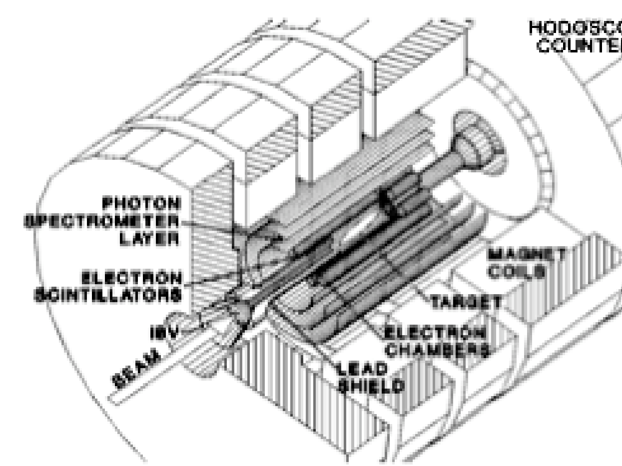


Hinks & Pontecorvo



Crystal Box



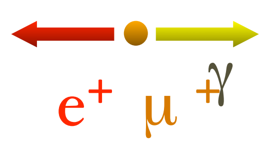


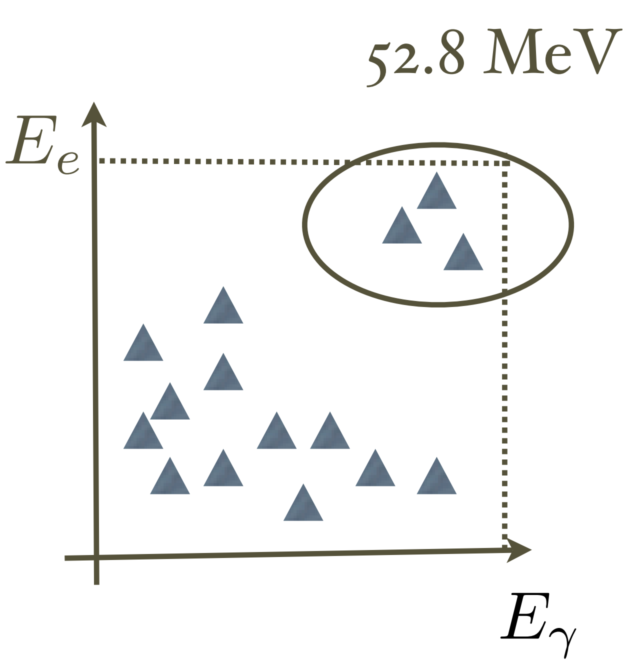
MEGA

Each improvement linked to an improvement in the technology

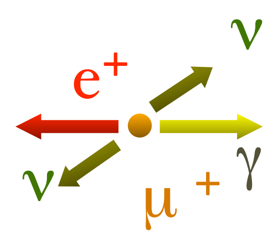
Signal and Background

"Signal"



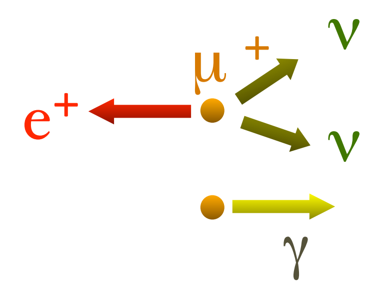


"Prompt"



$\mu \to e\bar{\nu}\nu\gamma$

"Accidental"



$\mu \to e\bar{\nu}\nu$

$\mu \to e\bar{\nu}\nu\gamma$

$e\mathcal{N} \to e\mathcal{N}\gamma$

$e^+e^- \to \gamma\gamma$

$B_{Prompt} \sim 0.1 * B_{acc}$

$B_{acc} \sim R_\mu \, \Delta E_e \, \Delta E_\gamma^2 \, \Delta\theta^2 \, \Delta t$

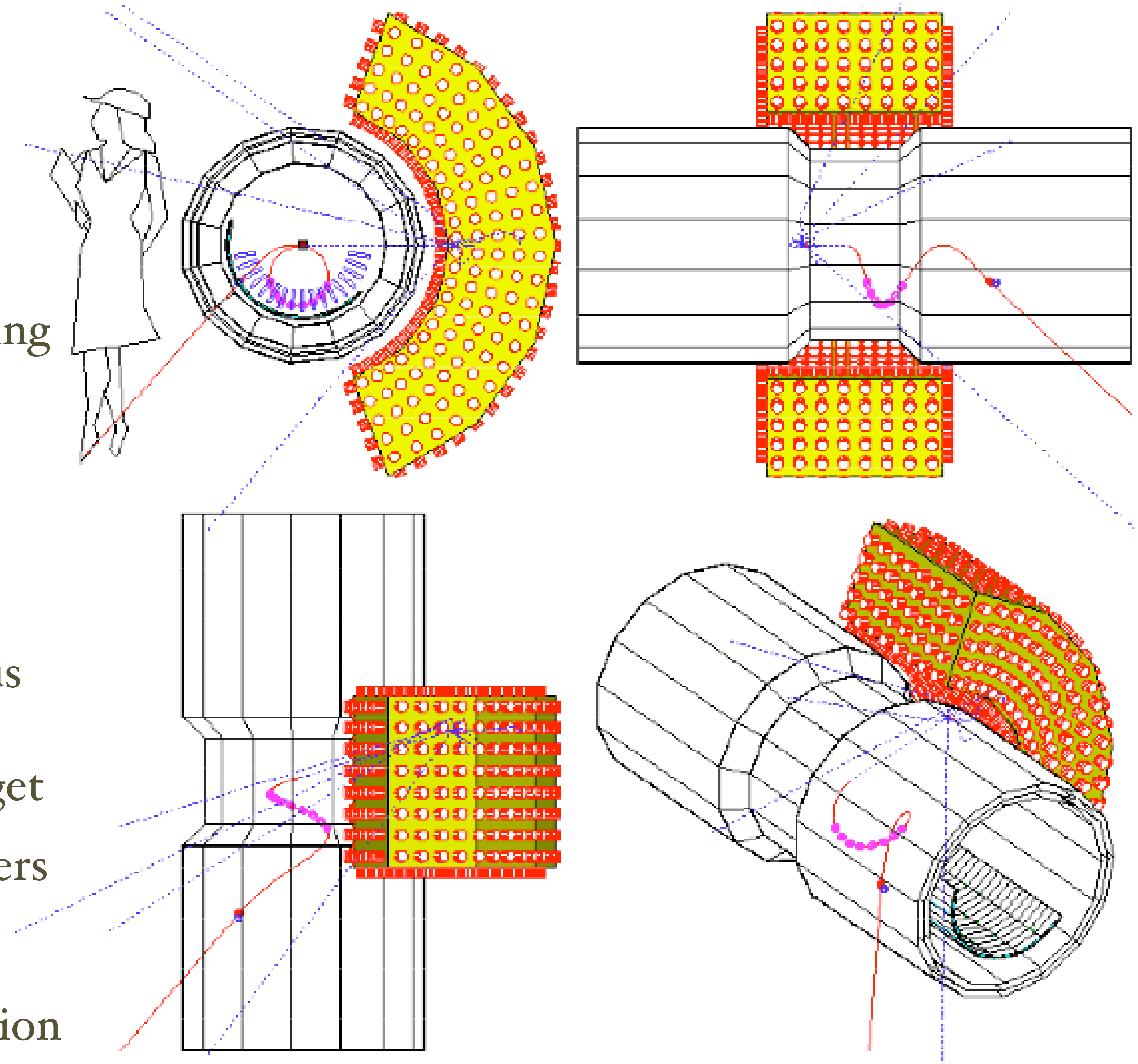
The accidental background is dominant and it is determined by the experimental resolutions

View of a Monte Carlo simulated event:

the photons enters the LXe calorimeter and the positron is measured by the drift chambers + timing counters.

Positron: energy, Momentum and timing

Photon: energy, direction and timing



Stopped μ-beam: up to 10^8 μ /sec

The presently most intense continuous muon beam in the world, PSI (CH) is brought to rest in a 100 μm mylar target

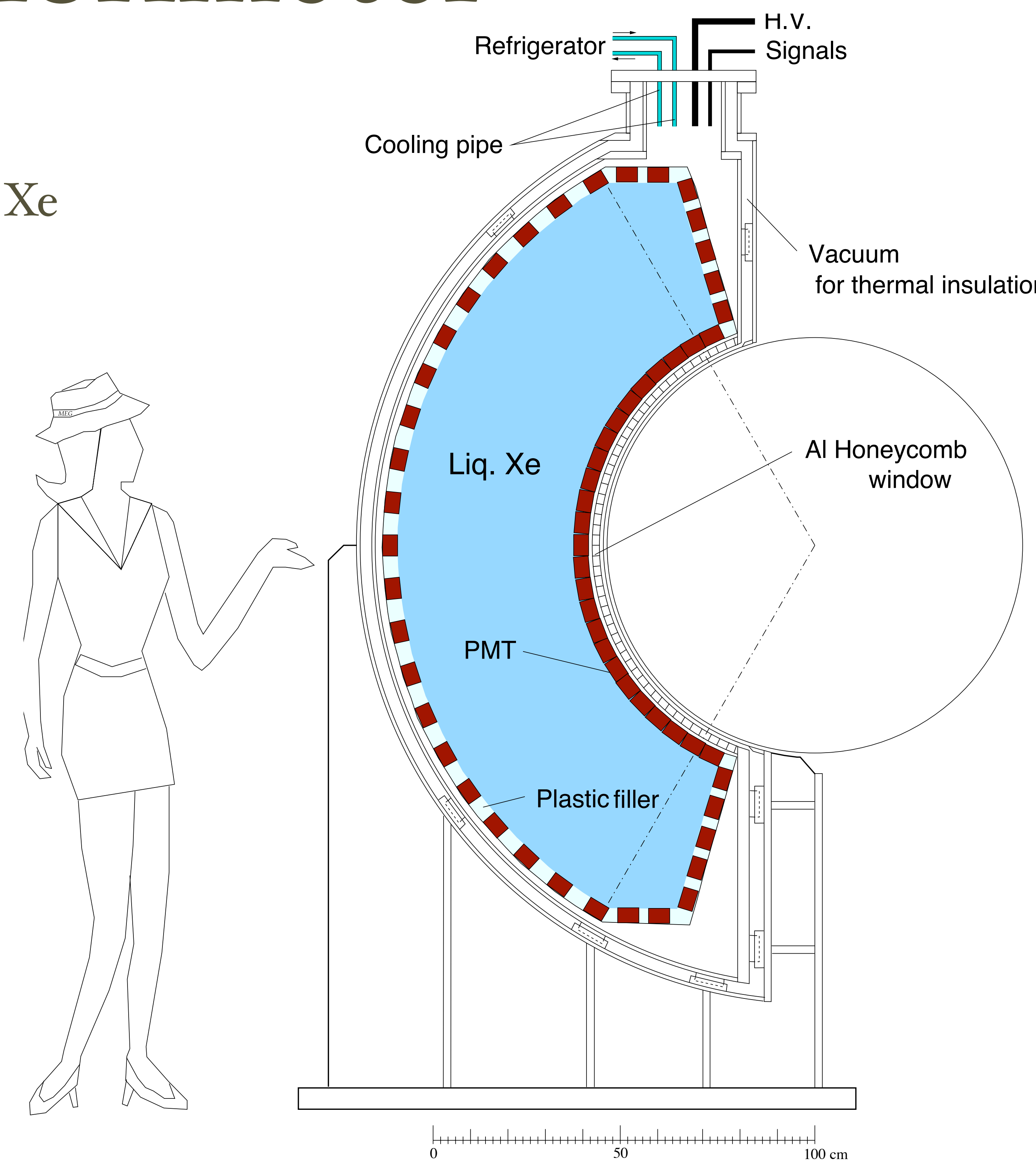
Solenoid spectrometer & drift chambers

Timing Counter for e+ timing

Liquid Xenon calorimeter for γ detection (scintillation)

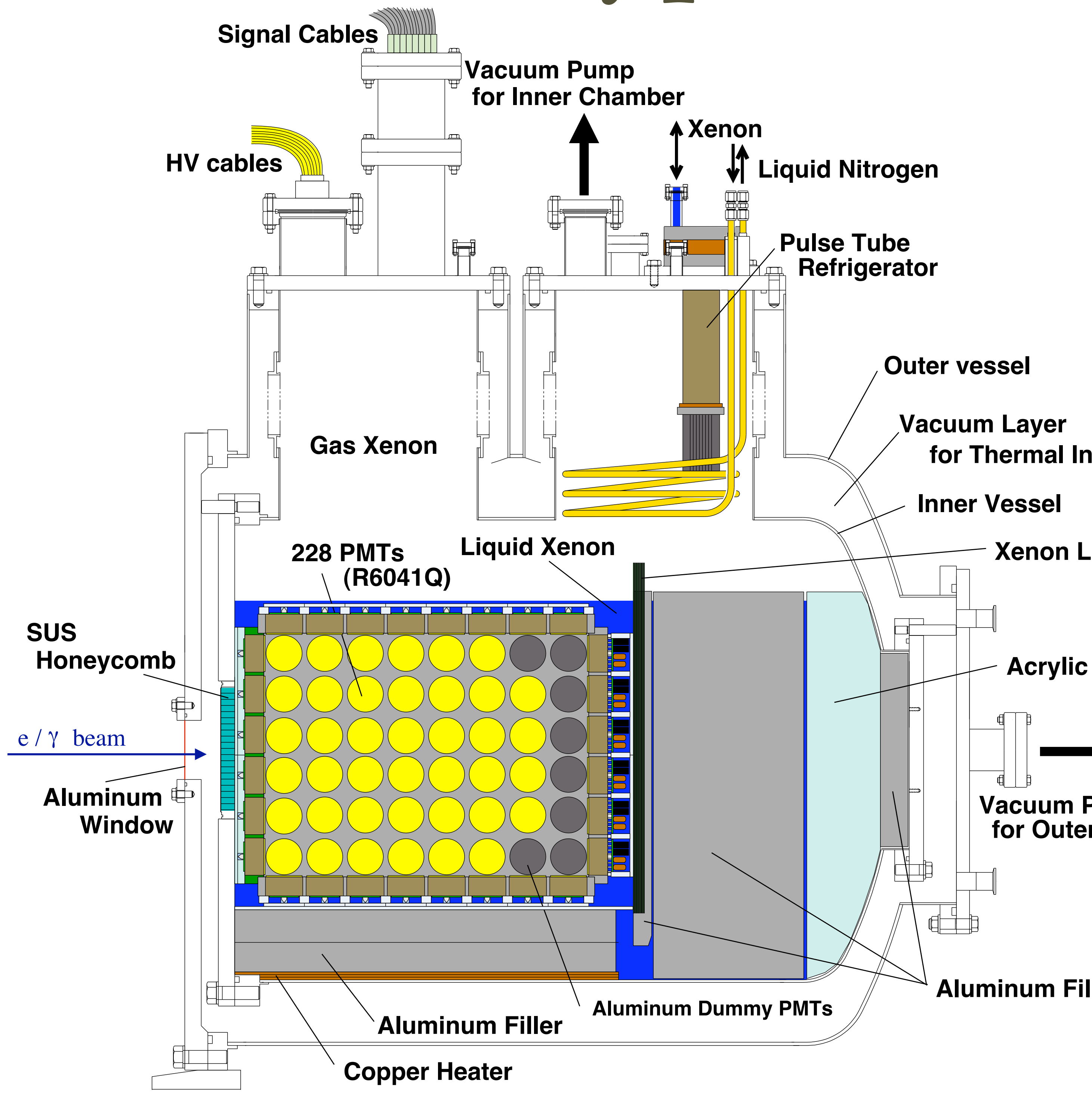
The calorimeter

- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
  - 10 % solid angle
  - 65 < r < 112 cm
  - $|\cos\theta| < 0.35$ $|\varphi| < 60^{o}$
- Only scintillation light
- Read by 848 PMT
  - 2" photo-multiplier tubes
  - Maximum coverage FF (6.2 cm cell)
  - Immersed in liquid Xe
  - Low temperature (165 K)
  - Quartz window (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
  - Pileup rejection



Xe Calorimeter Prototype

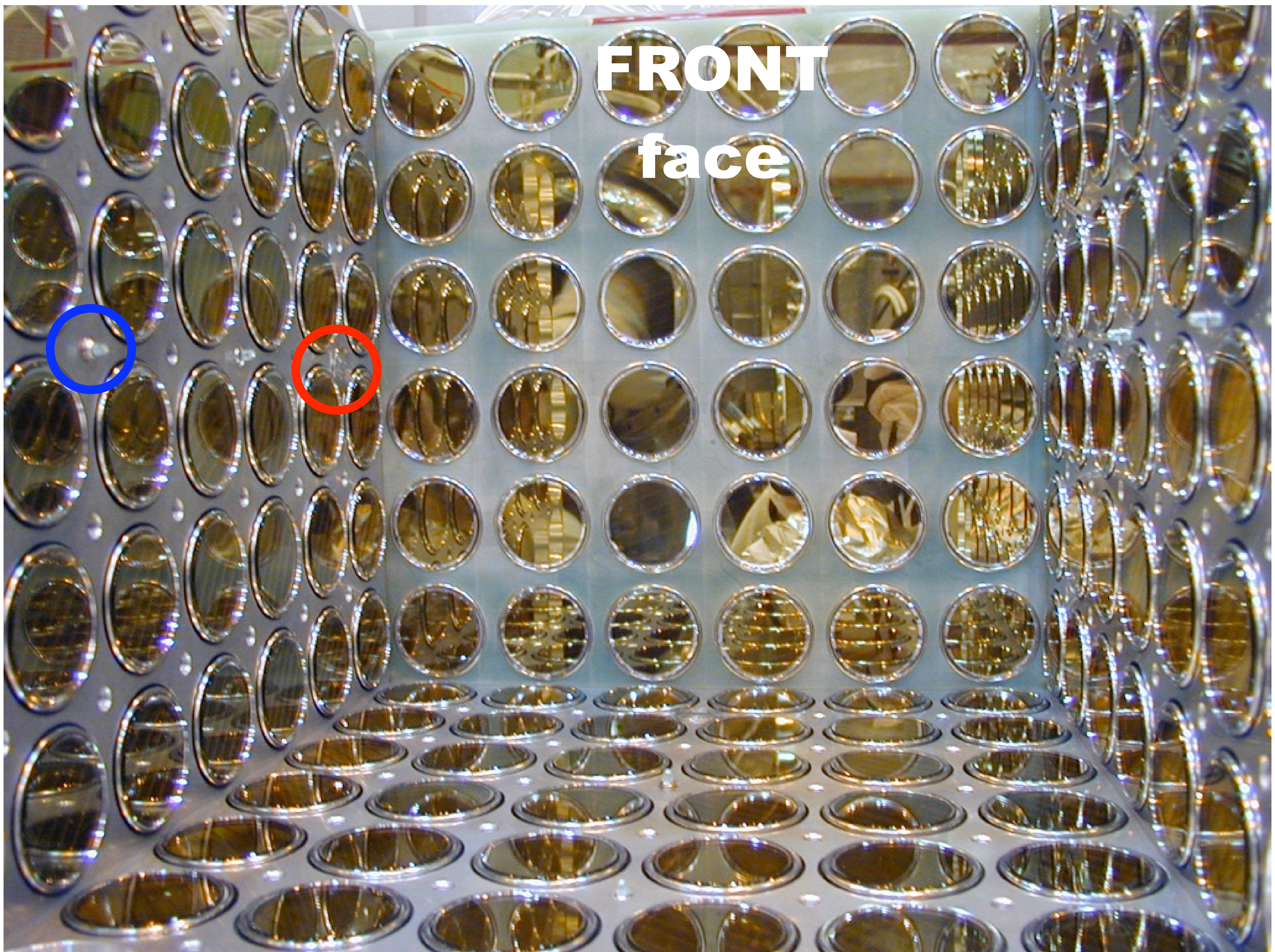
- 40 x 40 x 50 cm^3
  - 228 PMTs, 100 litres Lxe
- HAMAMATSU R6041 & R9288
  - Rb(K)-Cs-Sb photocathode
  - Mn layer/al fingers (resistivity at low T)
  - Quartz window
  - Metal channel dynode
- Used for the measurement of:
  - Test of cryogenic and long term operation
  - Energy/Position/Timing resolution



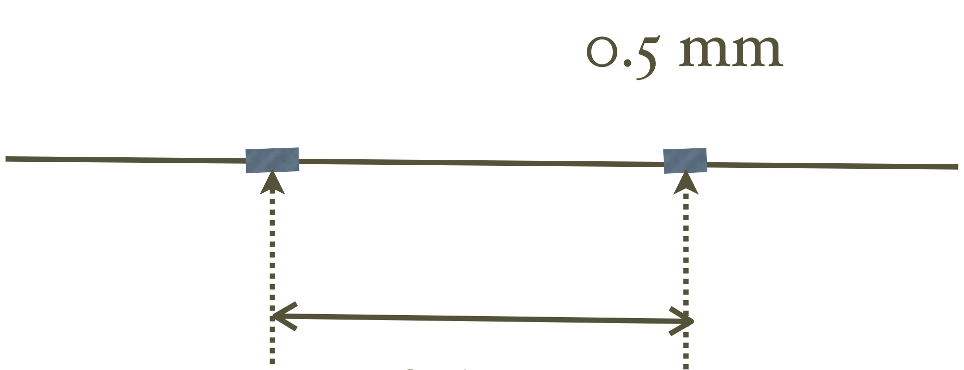
Biggest existing LXe calorimeter

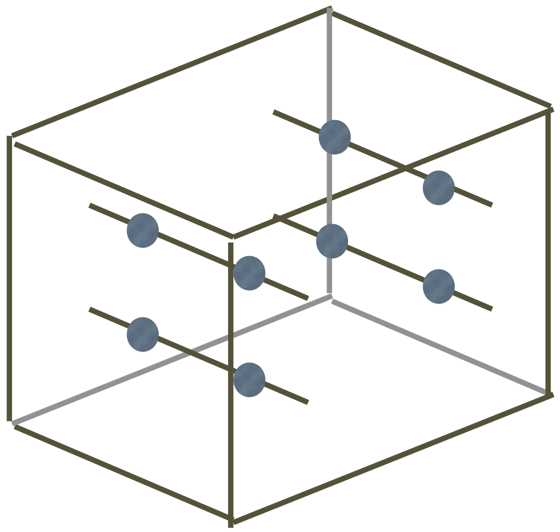
The LP from “inside”

α-sources and LEDs used for PMT calibrations and monitoring



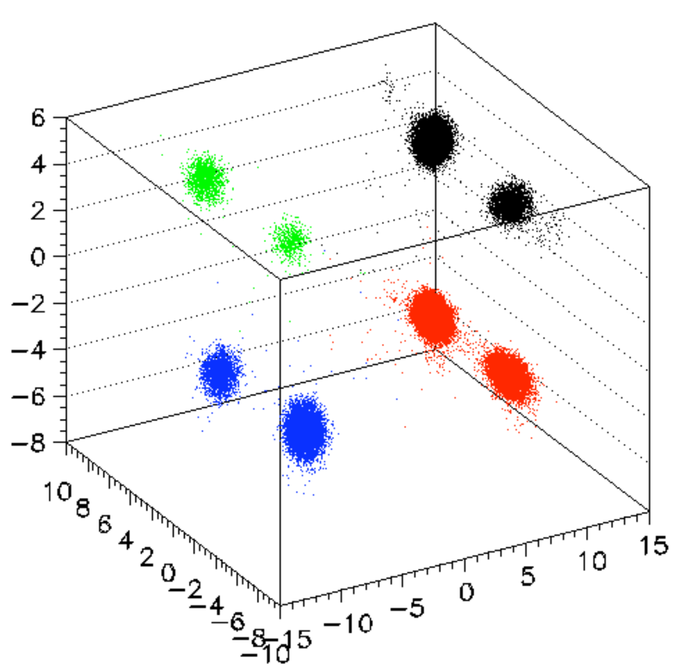
- Home-made Polonium alpha sources
- 50 Bq/each
- 50 micron tungsten wires
- exploit the uniqueness of this homogeneous device

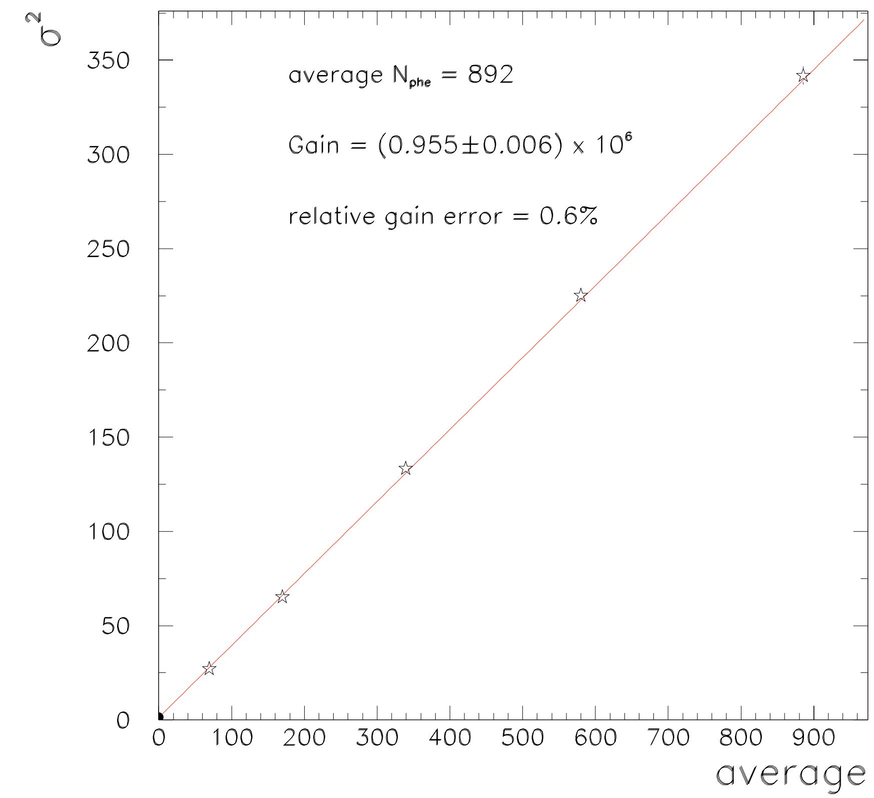


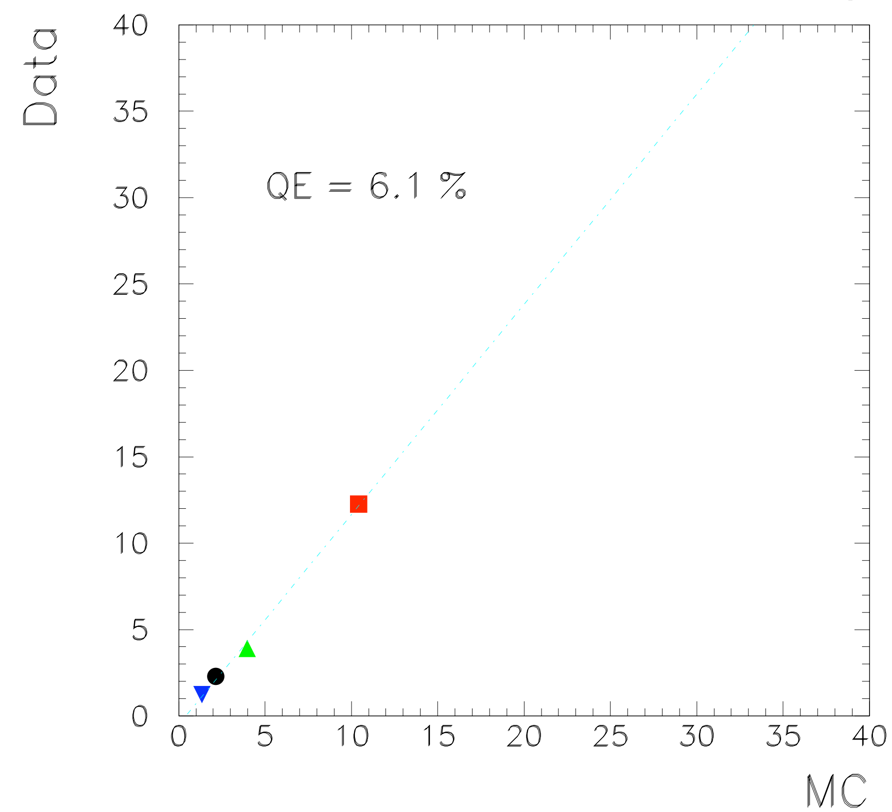


Gain and QE determination

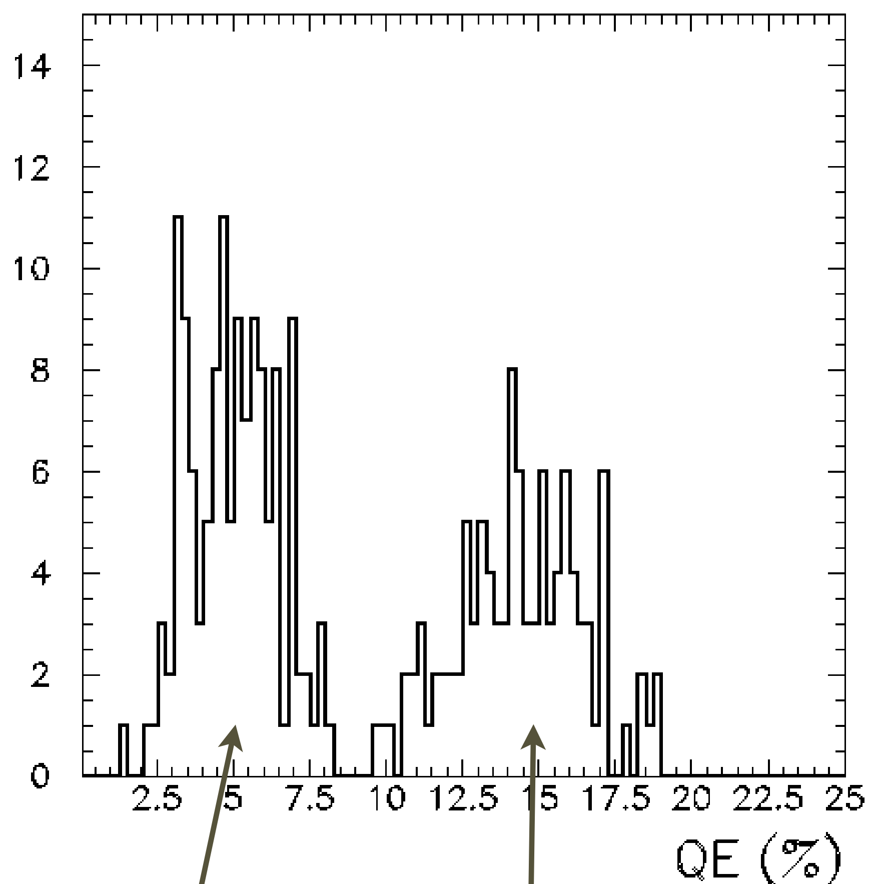
- Masurements of light from LEDs:
  - $\sigma^2 = g\,(q - q_0) + \sigma_0^{\,2}$
  - Absolute knowledge of the GAIN of ALL PMTs within few percents
  - $g = 10^6$ for a typical HV of 900 V
- QEs determined by comparison of alpha source signal in cold gaseous xenon and MC determined at a 10% level





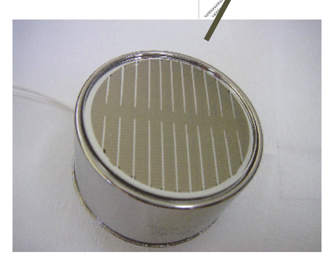


Computation of QEs



First Ver.

Second Ver.



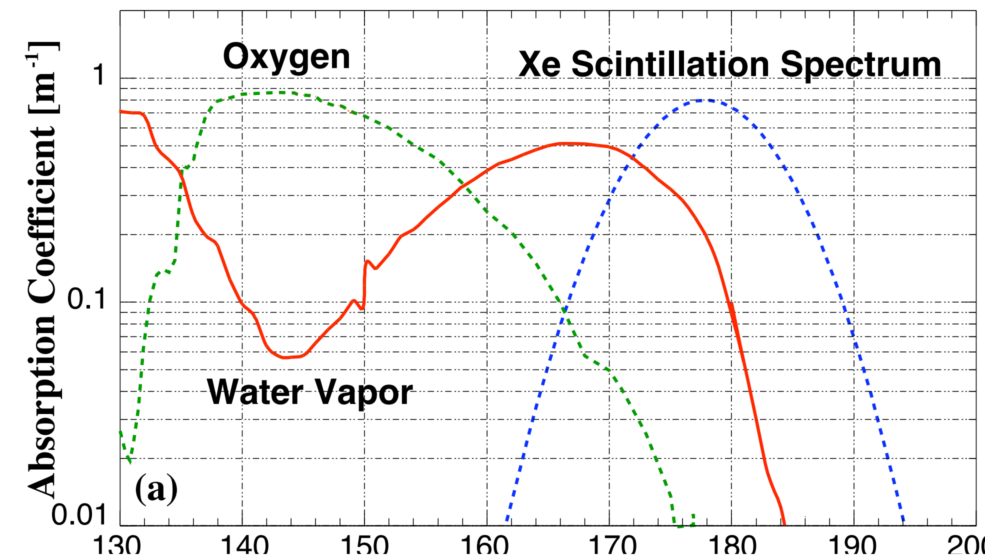
Final Ver.

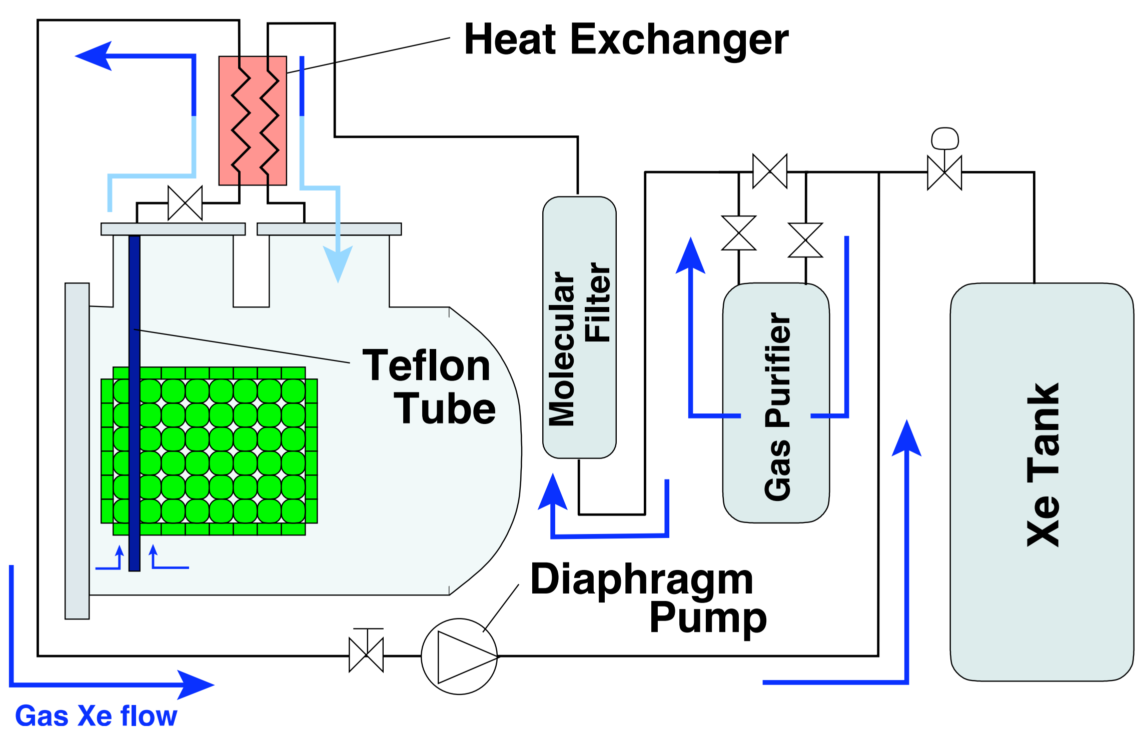
Photocathode	Rb-Cs-Sb	K-Cs-Sb	K-Cs-Sb
Material to reduce surface R	Mn layer	Al Strip	Al Strip (doubled)
Q.E. @ 165K	~5%	~15%	~15%

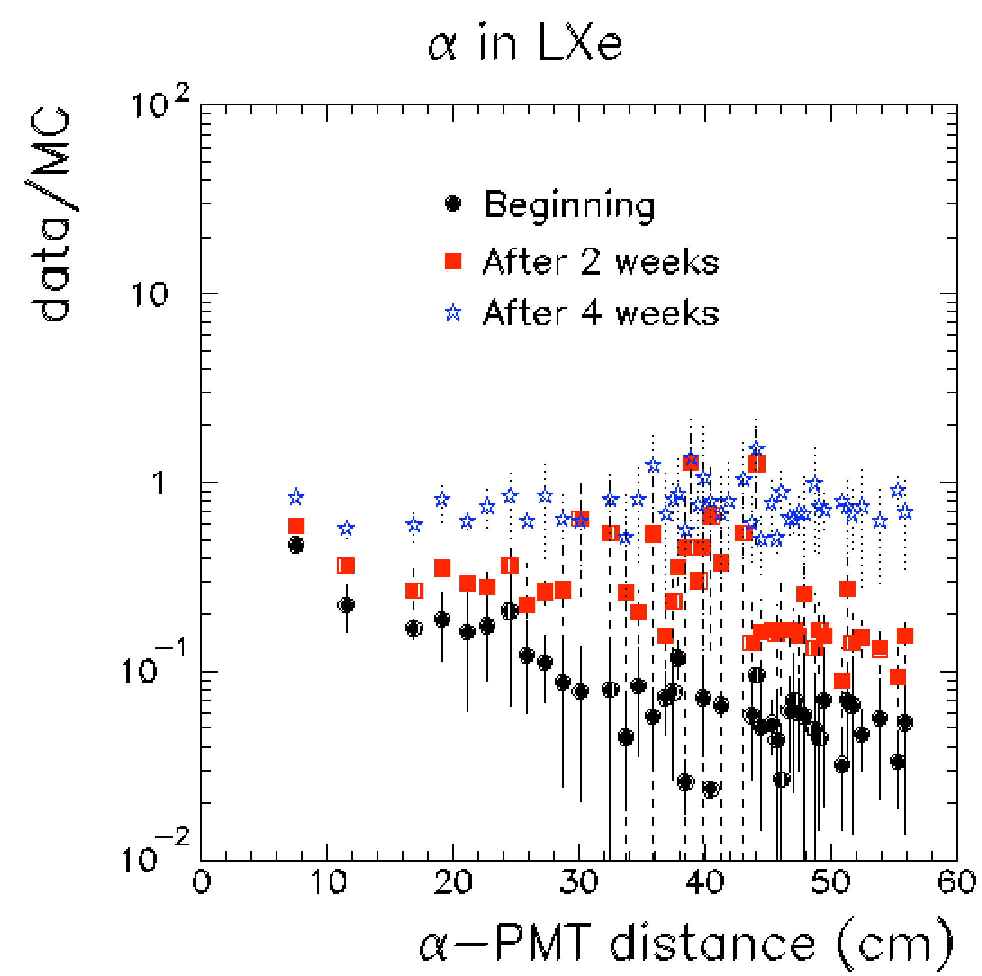
- Clearly distinguish the two types of PMT
- A third version envisaged for the final detector
  - strict collaboration with Hamamatsu photonics
  - tests performed in Pisa & Tokyo LXe test facilities
  - Better performance at high rate at LXe temperature
    - doubled Al strips
    - Zener diode in bleeder circuit

Measurement of absorption

- Energy resolution strongly depends on absorption
- We developed a method to measure the absorption length with alpha sources
- We added a purification system (molecular sieve + gas getter) to reduce impurities below ppb

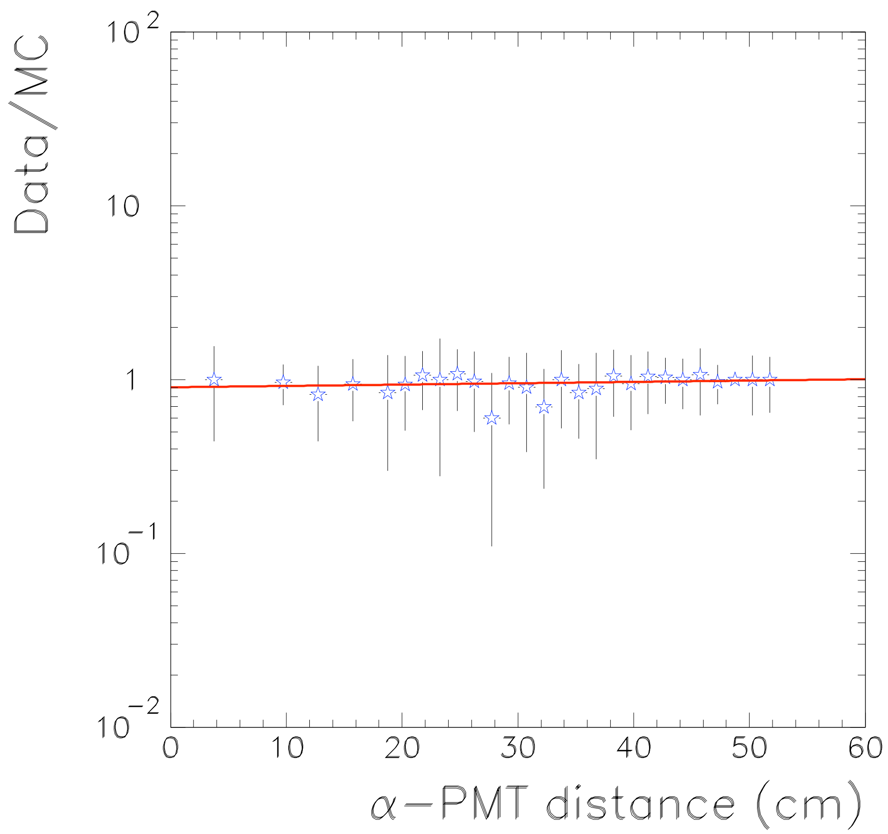


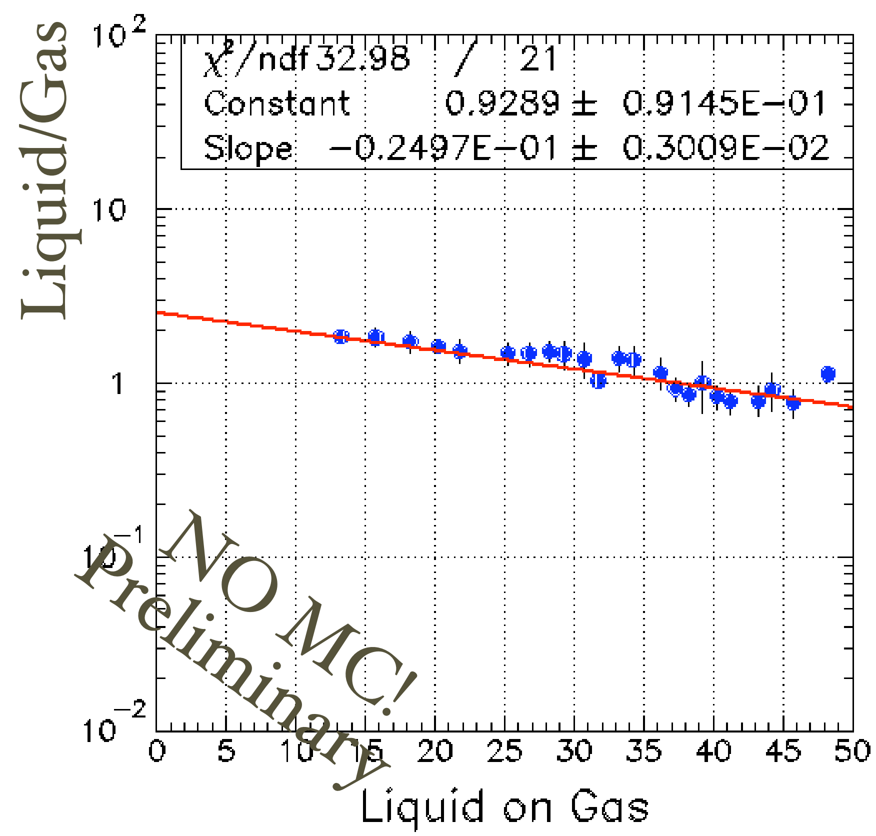




λ_{Abs} measurement

- It is possible to estimate a lower limit on the xenon absorption length
- Typical plots shown
  - λ_{Abs} > 125 cm (68% CL) or λ_{Abs} > 95 cm (95 % CL)
  - LY ~ 37500 scintillation photons/MeV (0.9 NaI)





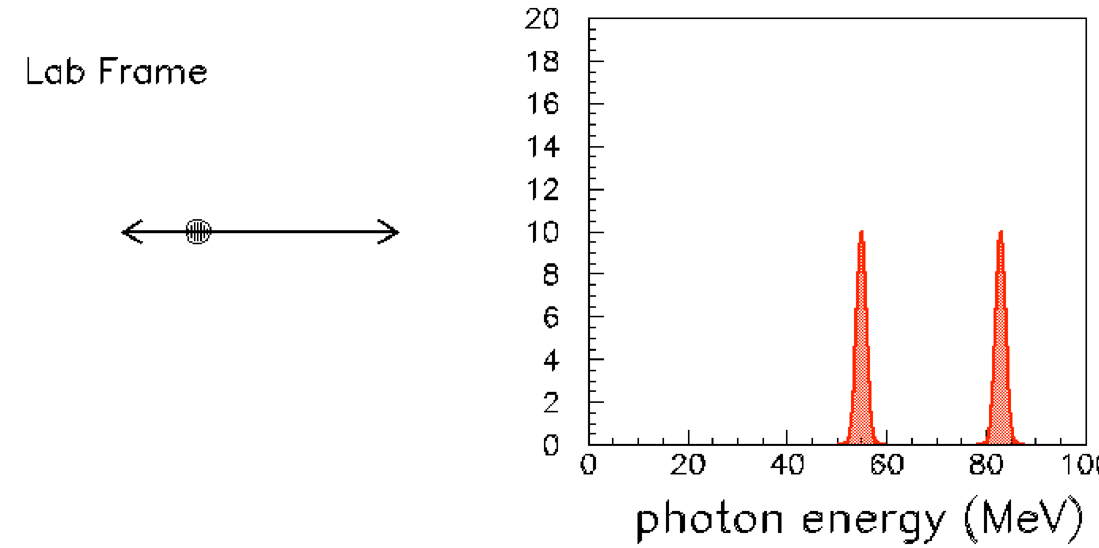
Attenuation = Rayleigh

$\lambda_{Att} \sim 40$ cm

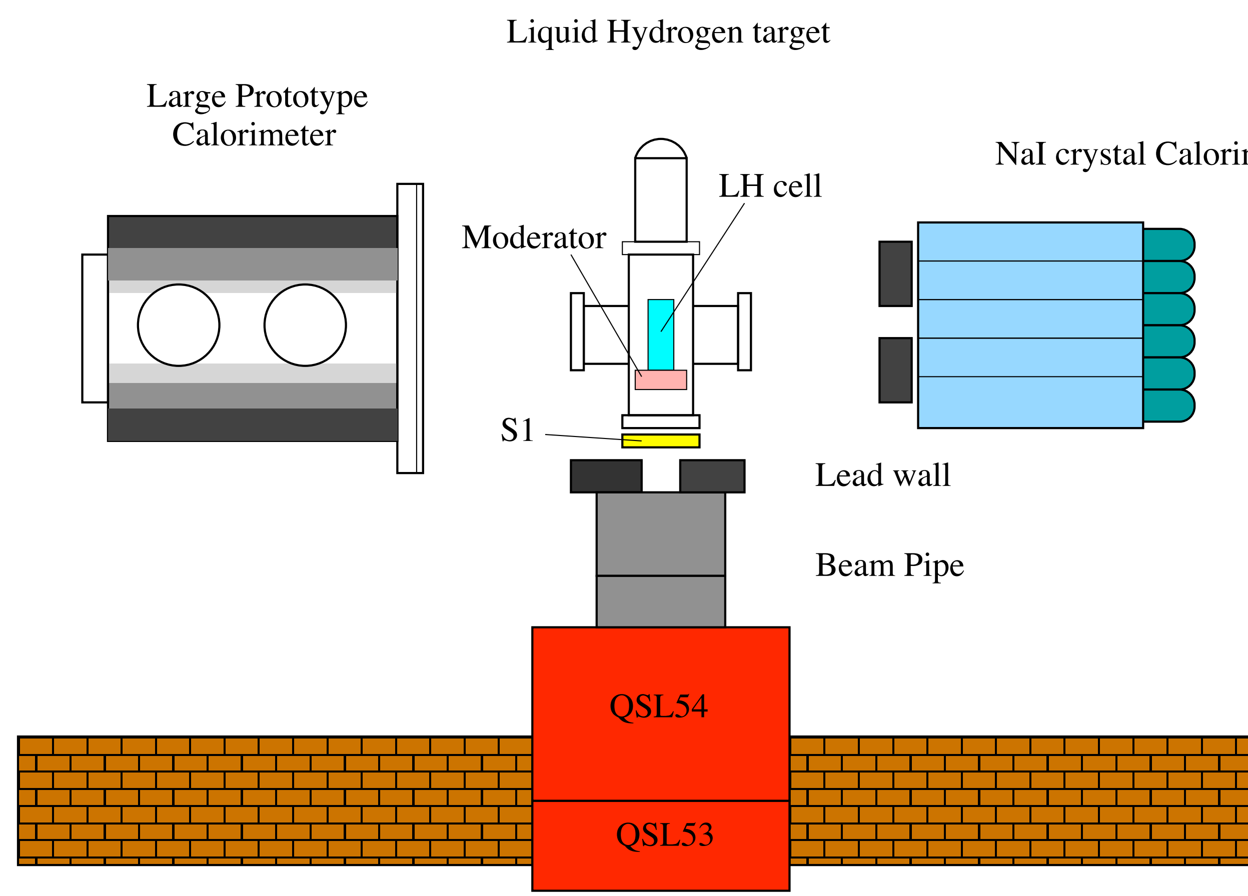
L.Y.(liquid) $\sim 3 \times$ L.Y.(gas)

Energy resolution measurement

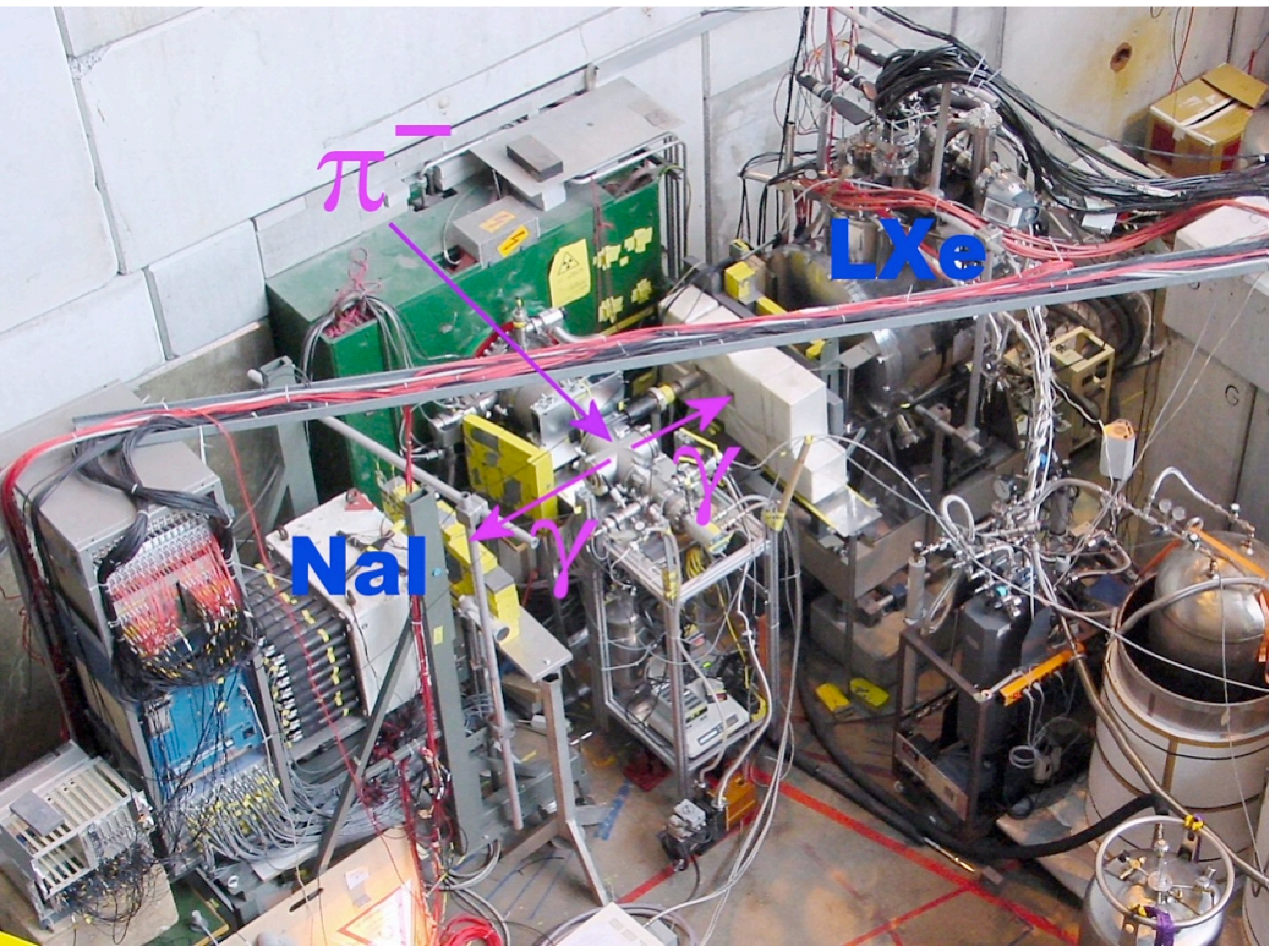
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$



- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV

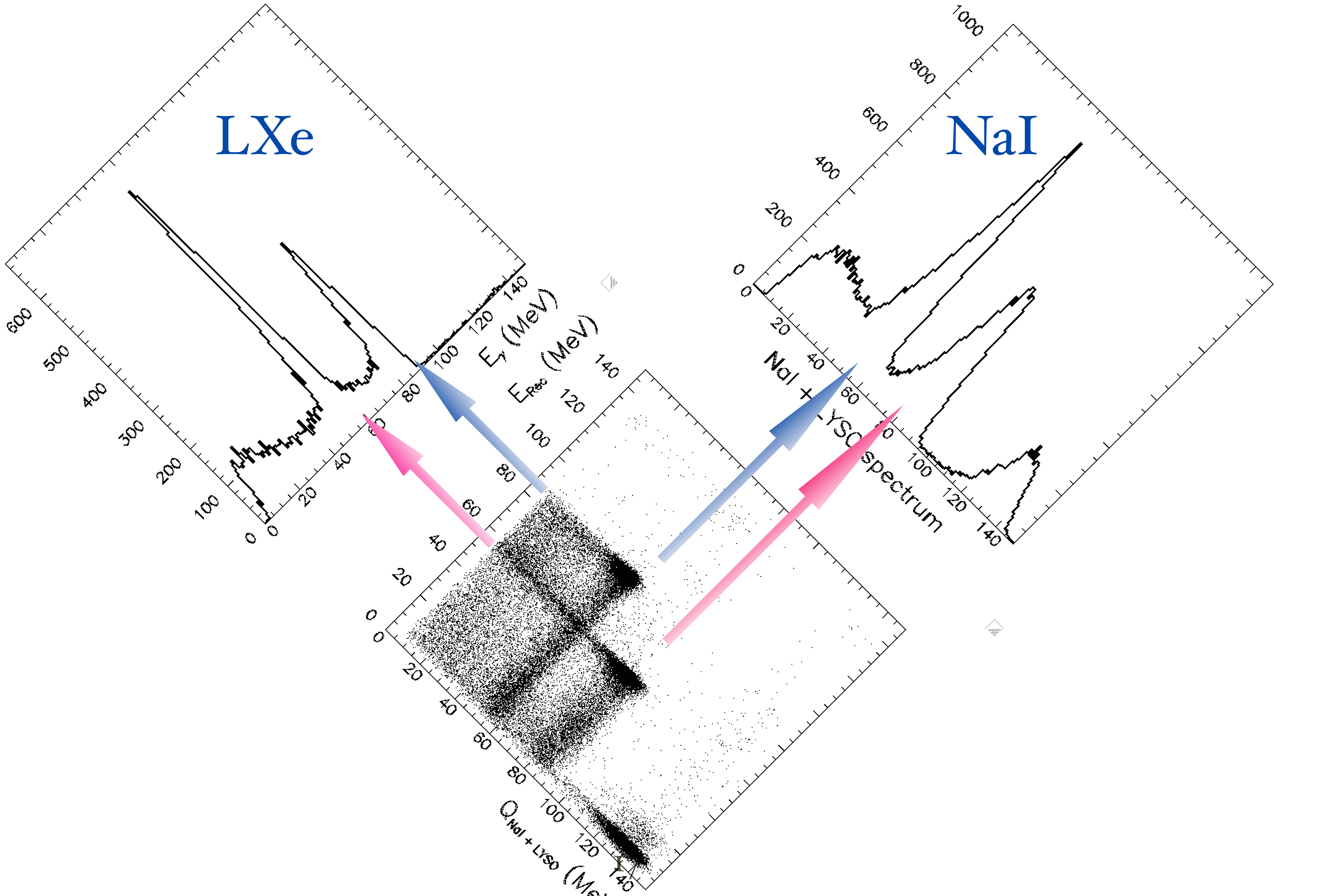


- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)



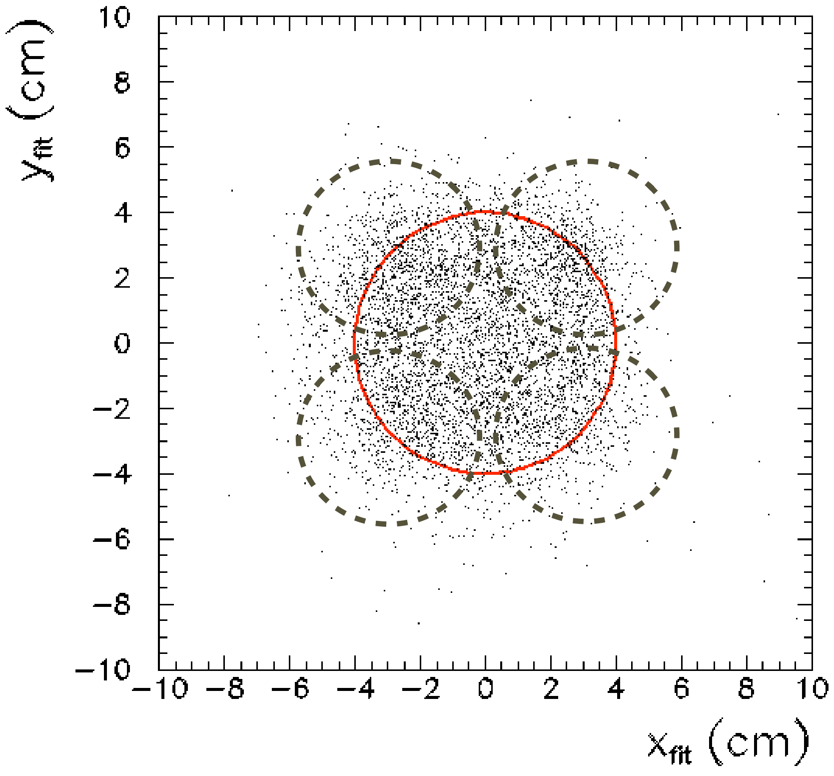
π⁻
LXe
γ
γ
NaI

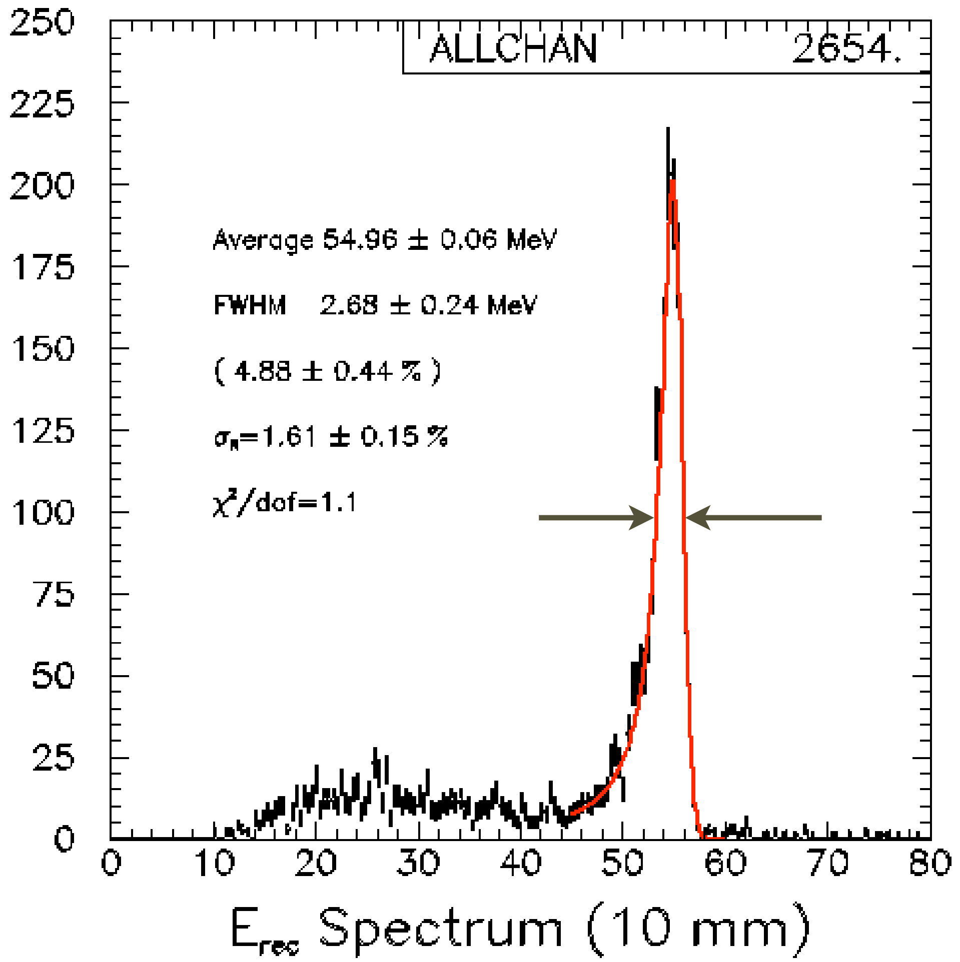
- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)



Resolution @ 55 MeV

- Select negative pions in the beam
- 65 MeV < E(NaI) < 95 MeV
- Collimator cut (r < 4 cm)



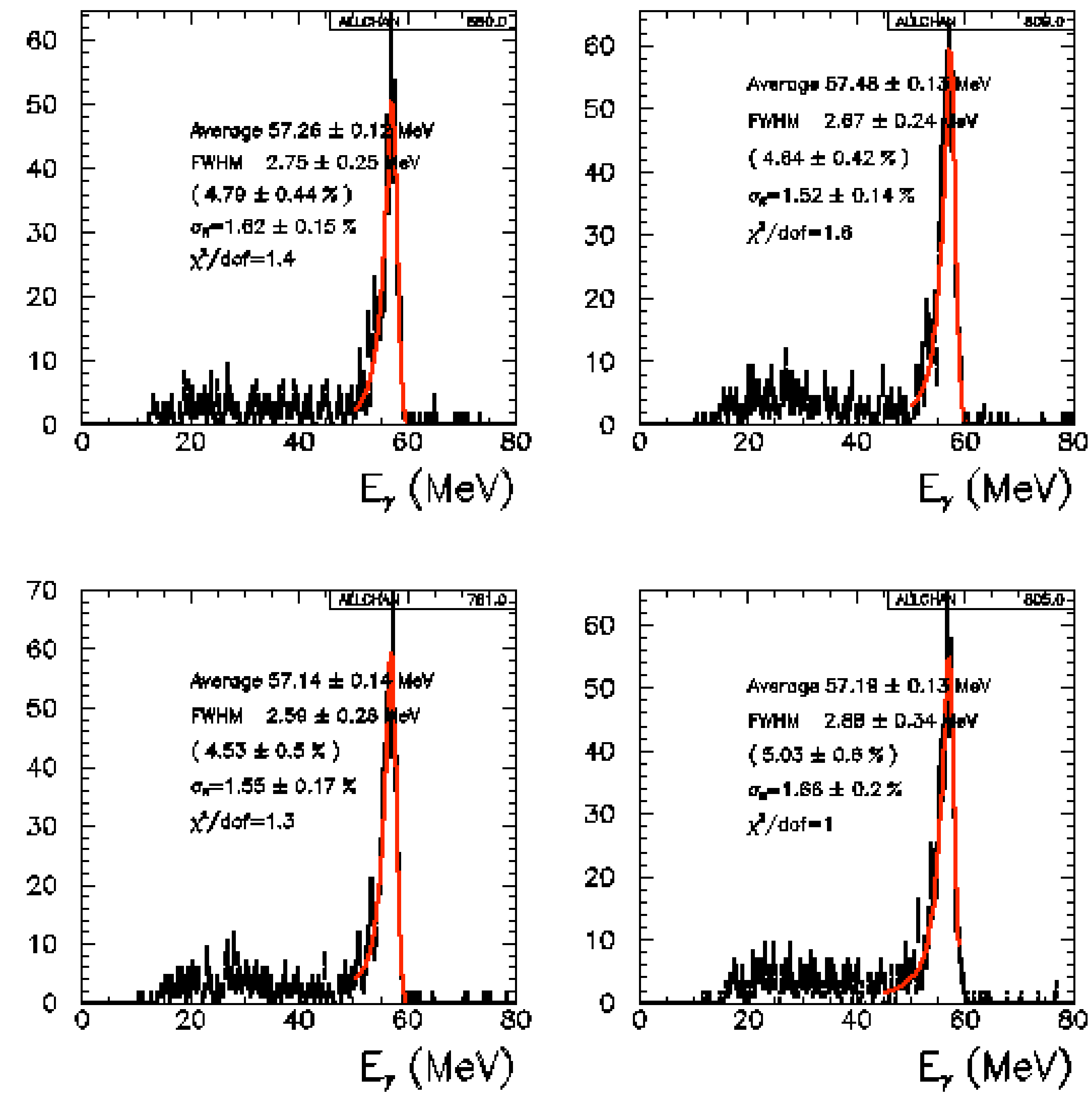


Resolution (FWHM)
(4.9 ± 0.4) %

Position dependence

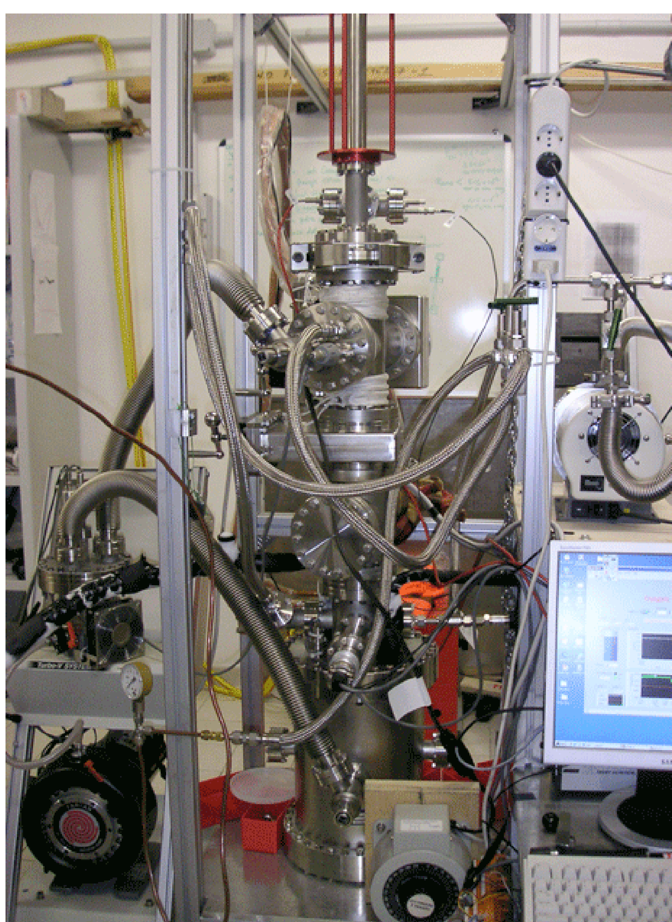
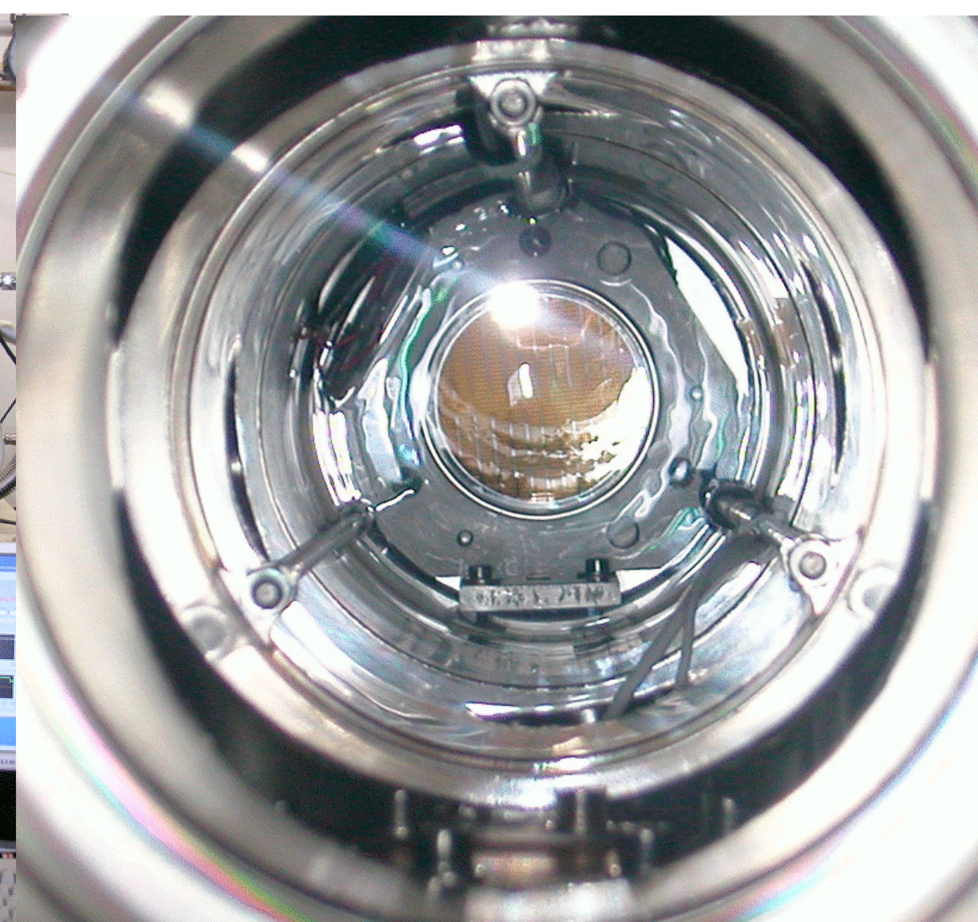
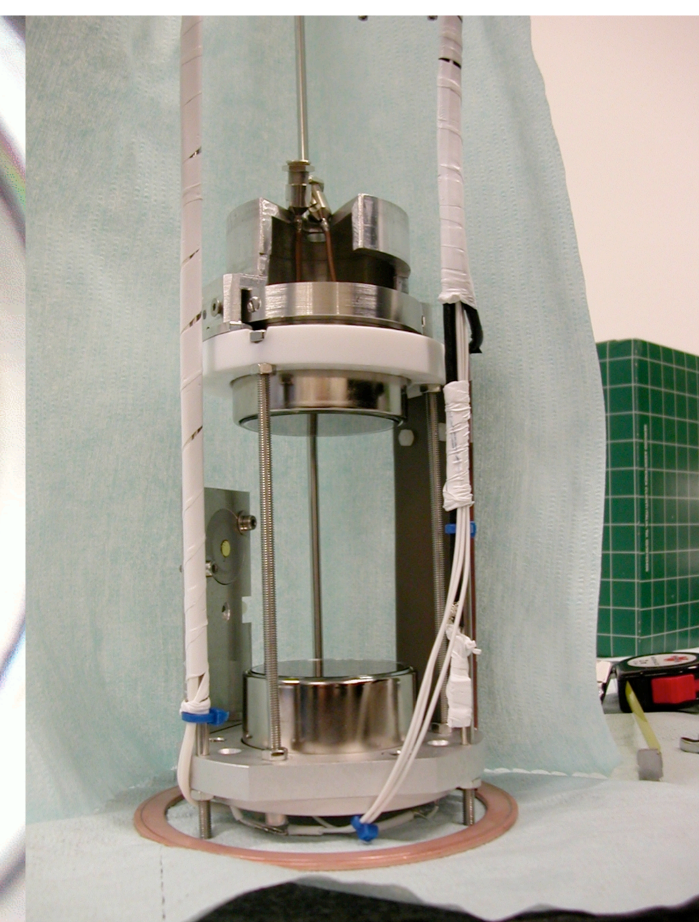
- small FWHM residual dependence
- no significant peak shift
- The resolution is always better than 5% FWHM

4.8%	4.6%
4.5%	5.0%



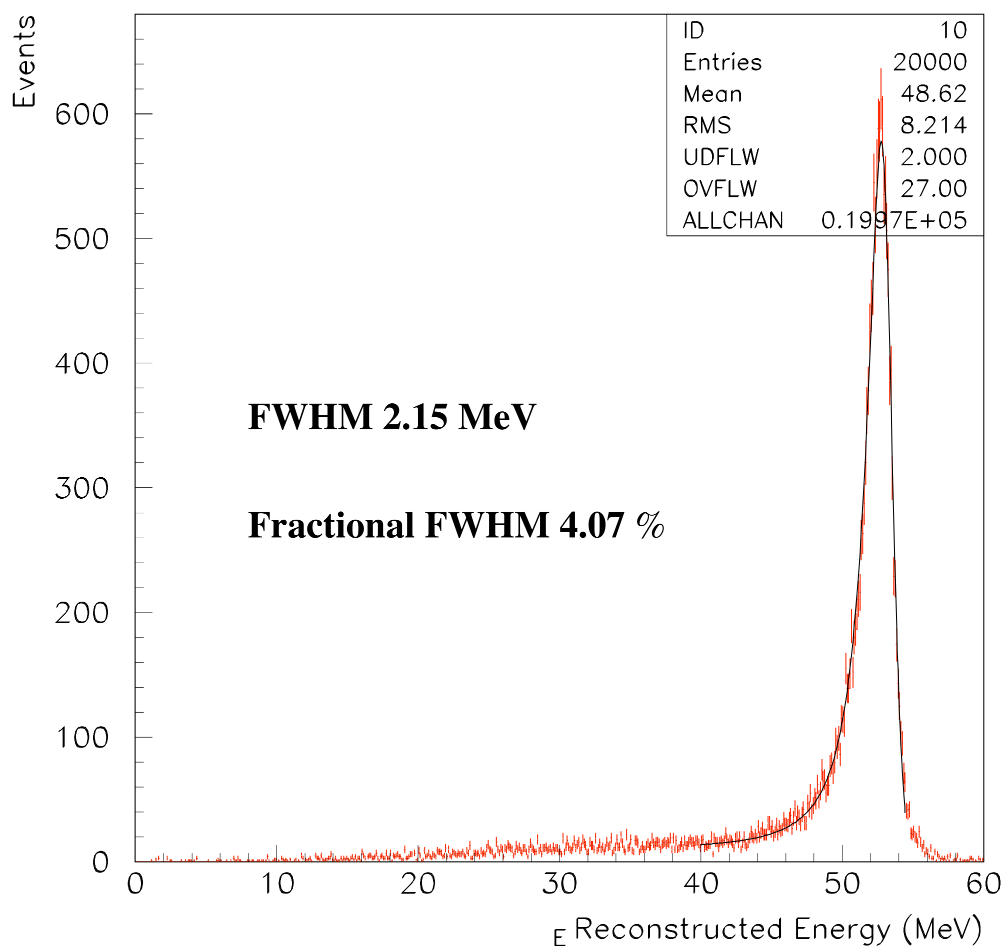
Conclusion

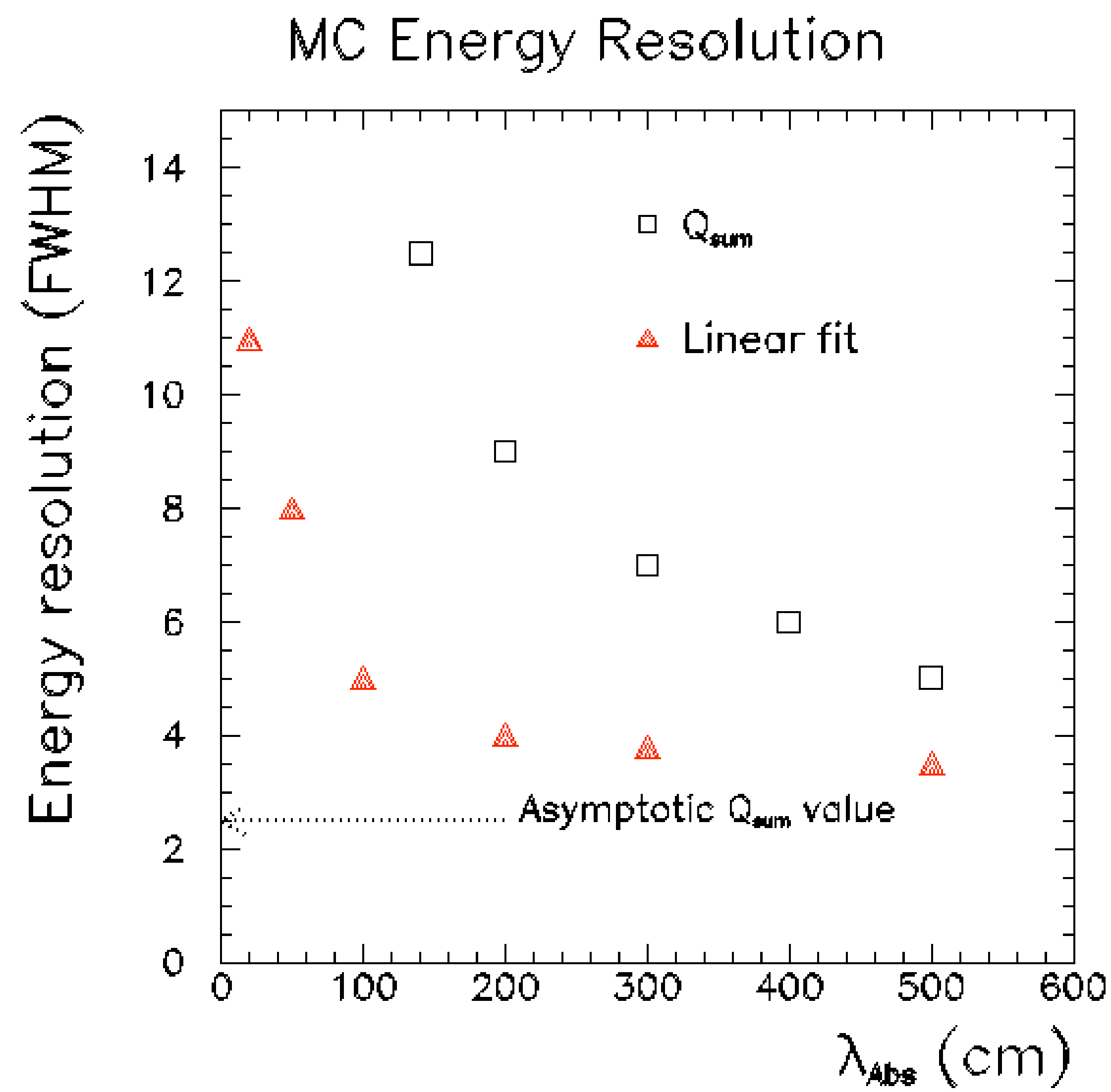
- The MEG experiment is expected to start engineering run in 2006
- Tests of the most advanced sub-detector were shown
  - Absorption length > 100 cm
  - Energy resolution < 5% FWHM at 55 MeV
  - Successful PMT and energy calibration and monitoring (1/4)
- First application (to our knowledge) of sources on wires
- Tests of 800 PMTs for the final calorimeter ongoing in PSI / Pisa / Tokyo

MC simulation

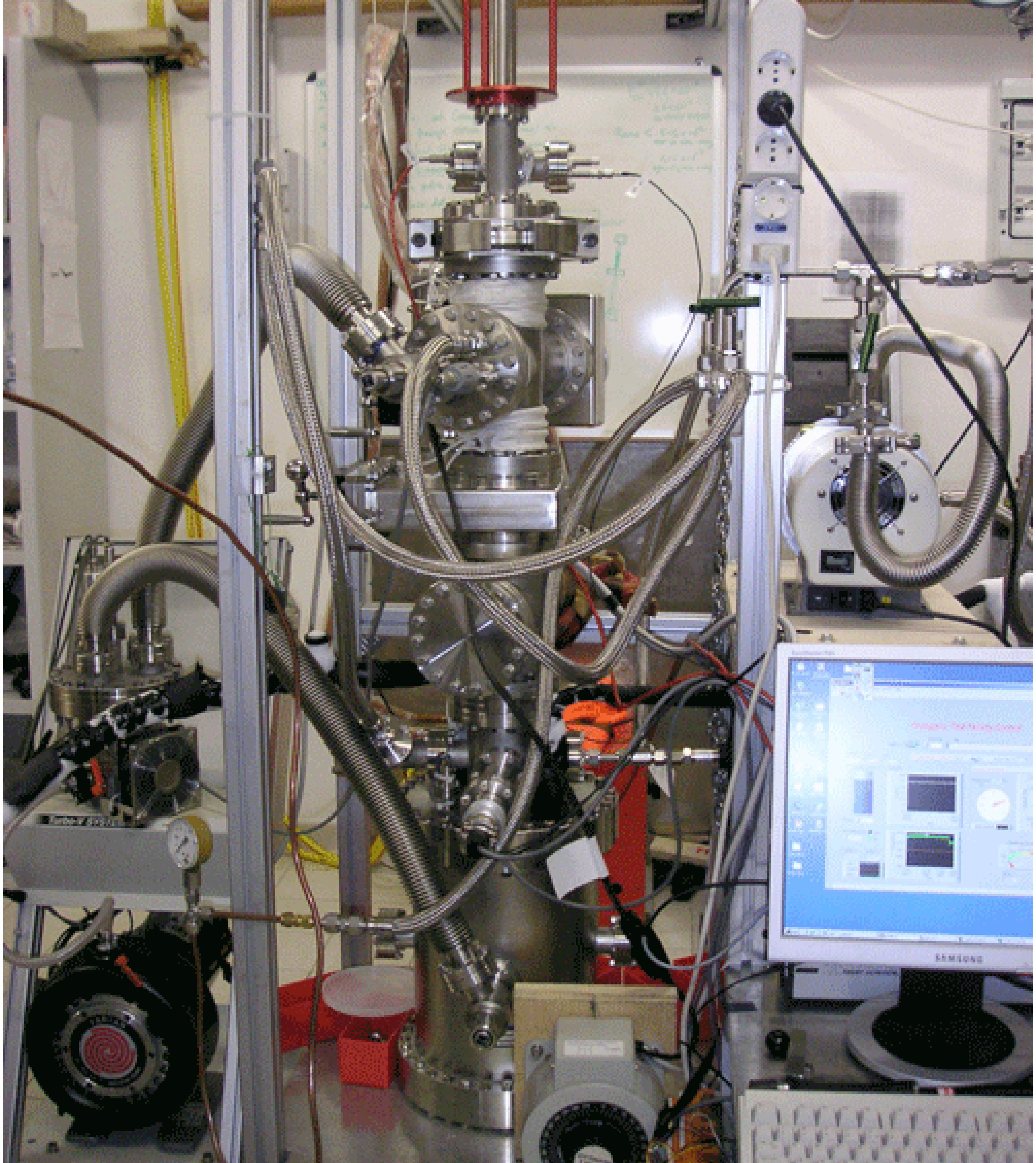
Energy resolution heavily depends on absorption





Build and test a Large Prototype

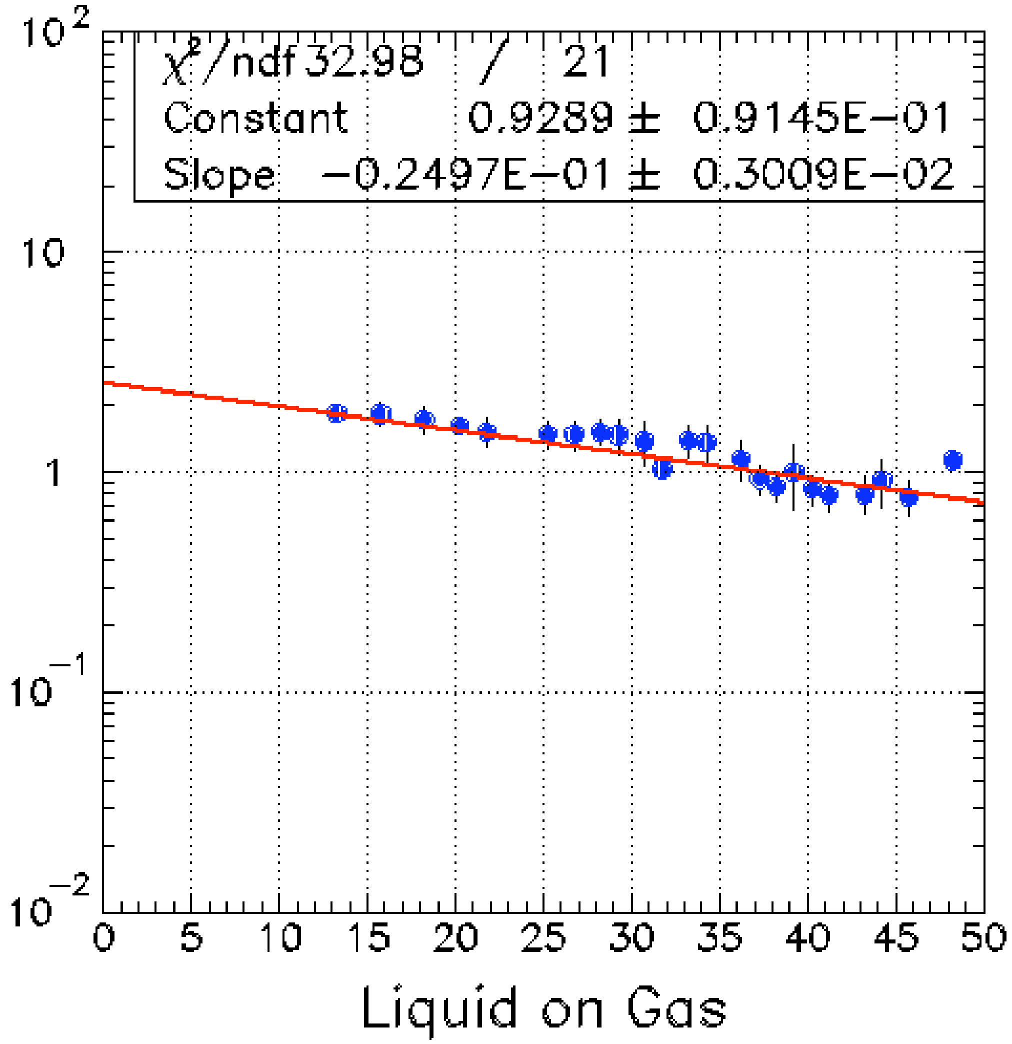
Optical (and scintillation!!) properties poorly known because done with small cryogenic chambers


SAMSUNG


100 ml

Attenuation measurement

- Light attenuation is dominated by Rayleigh scattering
- The residual slope, comparing Gas data to Liquid data (No MC!), is linked to that

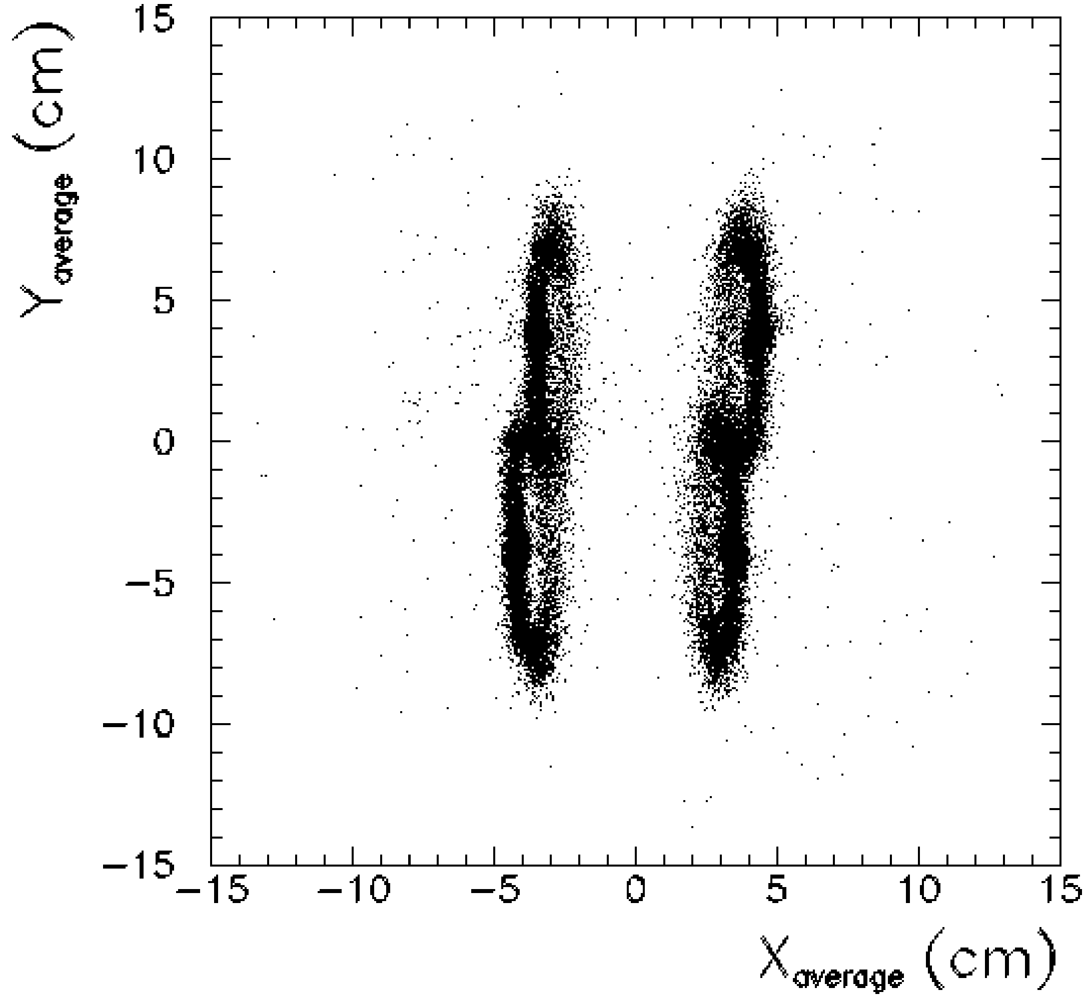


$$\lambda_{\mathrm{Att}} \sim 40 \text{ cm}$$

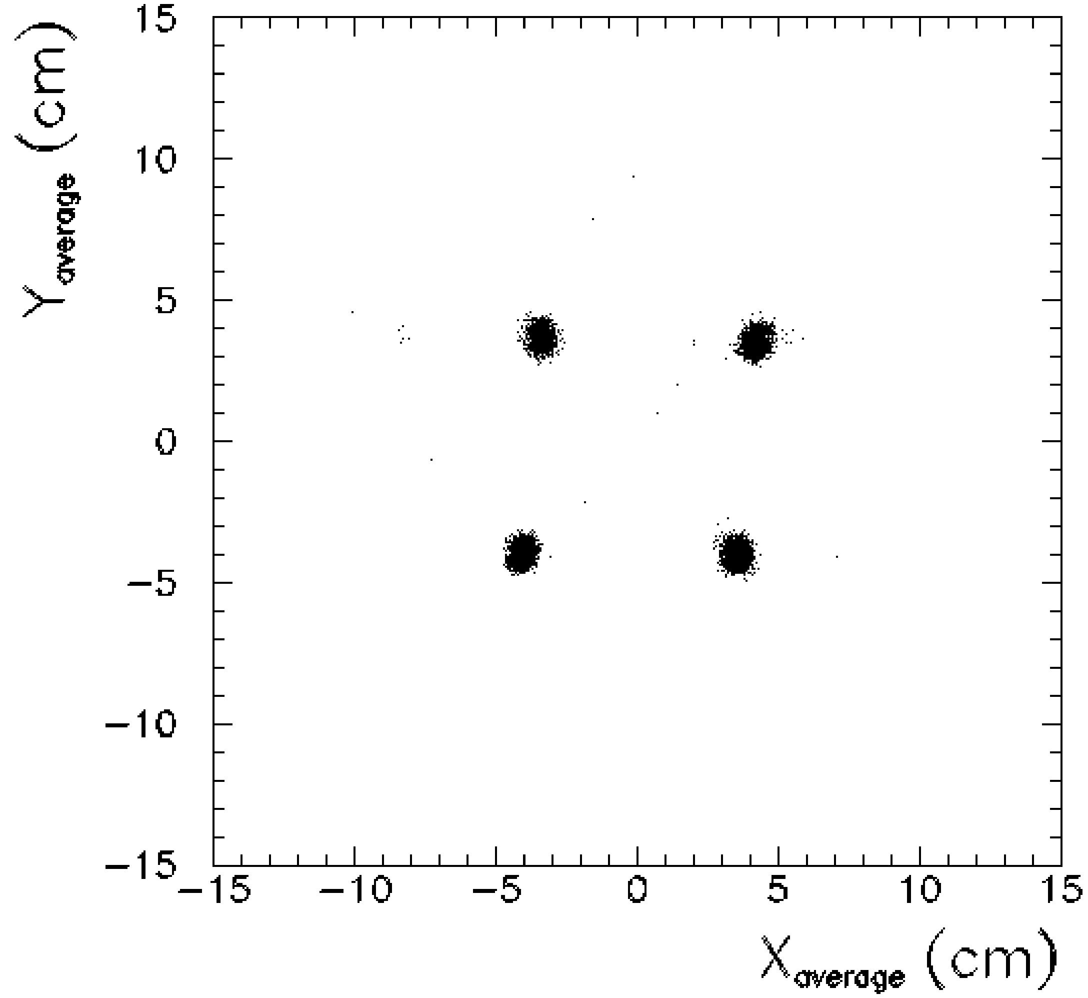
$$\text{L.Y.(liquid)} \sim 3 \times \text{L.Y.(gas)}$$

- Difference between liquid and gaseous xenon determined by alpha range
- The two wires on the front face are a little displaced

LXe ($R \approx 40\ \mu$m)



GXe ($R \approx 7$ mm)



MEG sensitivity

- Computation of the sensitivity based on the measured resolutions

FWHM E_γ/E_γ	5 %
FWHM E_e/E_e	0.9 %
$\delta t_{e\gamma}$	105 ps
$\delta\theta_{e\gamma}$	23 mrad

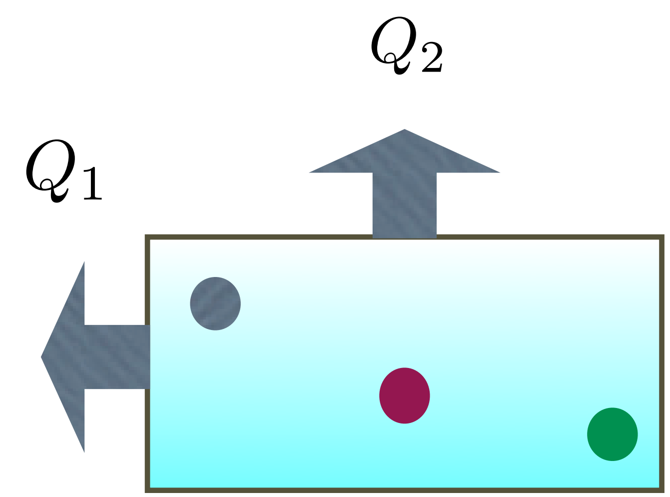
- The resolutions determine the accidental background
- For a given background we choose R(μ) and running time.
  - BG = 0.5 events
  - R(μ) = 1.2 10^7 μ/sec
  - T = 3.5 10^7 sec (2 years running time)
  - ⇒SES = 6 10^{-14} (1.7 10^{13} muons observed)
- NO candidate ⇒ BR(μ→eγ) < 1.2 10^{-13} @ 90% CL
- Unlikely fluctuation (4 events) ⇒ BR(μ→eγ) ≈ 2.4 10^{-13}

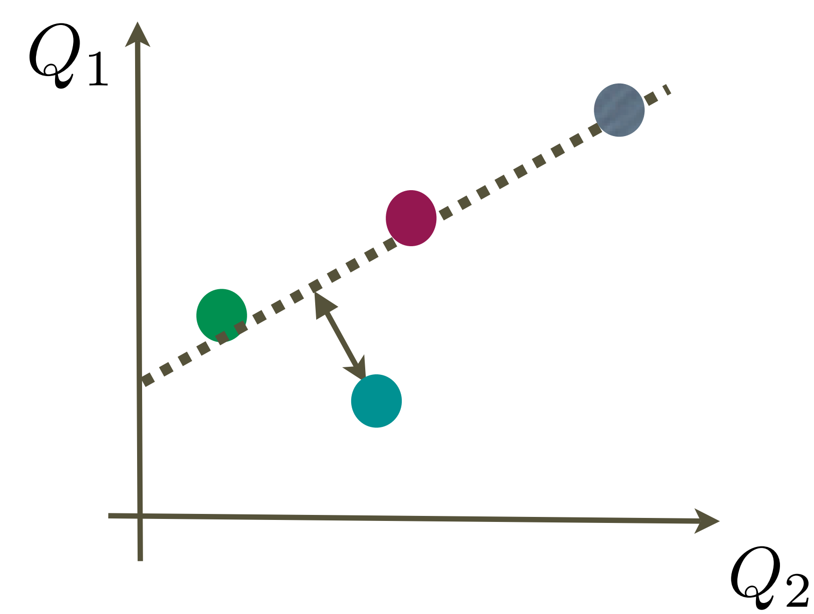
Conclusion

- The MEG experiment is expected to start engineering run in 2006
- Tests of the most advanced sub-detector were shown
  - Absorption length > 100 cm
  - Energy resolution < 5% FWHM at 55 MeV
  - Importance of PMT and energy calibration and monitoring
- Expected sensitivity at a level of 10^{-13}
- Space (and time) for improvements!

Energy estimate

- Easiest way is Q(sum) = $\sum_{i=1}^{N} Q_i$
  - Ideal for spherical detectors
  - Events at the center of the detector
  - Needs corrections for general shape detector
- "Linear Fit" method
  - $E = c + \sum_i c_i Q_i$
  - The weights are computed with MC events + minimization
  - χ^2 = distance from MC energy
  - Analytical minimization
- The performance of the "Linear Fit" is in general better, and as fast as Q(sum)





An example of γ spectrum

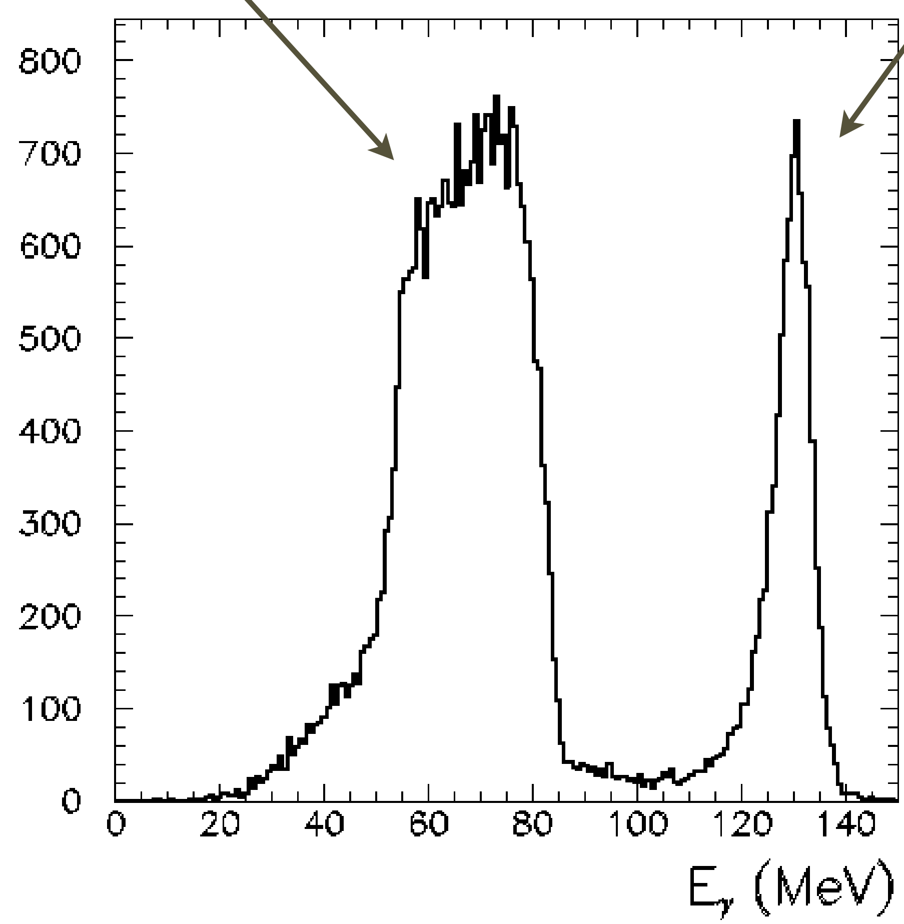
- Two gamma trigger configurations:
  - one-arm = RF .AND. S1 .AND. (NaI .OR. LXe)
  - two-arm = RF .AND. S1 .AND. NaI .AND. LXe
- Energy spectrum reconstructed in the LXe calorimeter prototype

$\pi^- p \to \pi^0 n$

$\pi^0 \to \gamma\gamma$

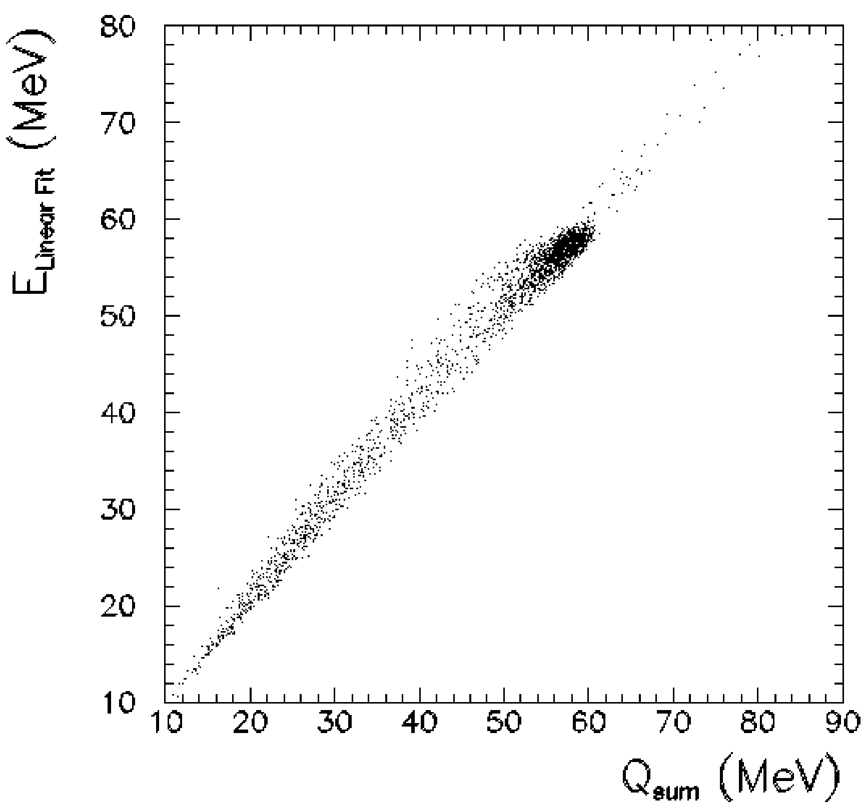
$\pi^- p \to \gamma n$

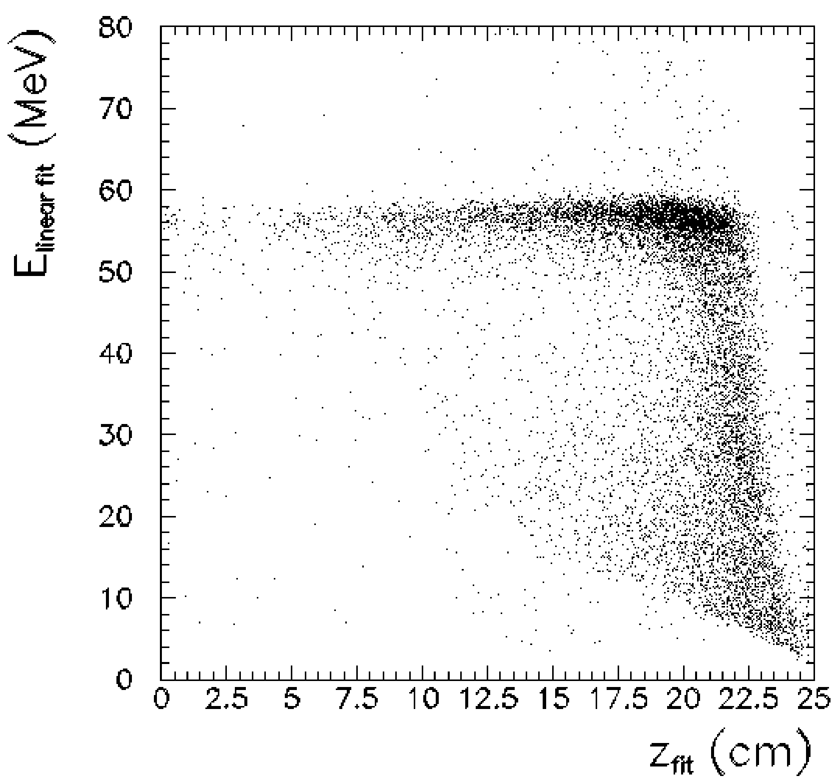
The energy scale is calibrated with all the peaks and AmBe source

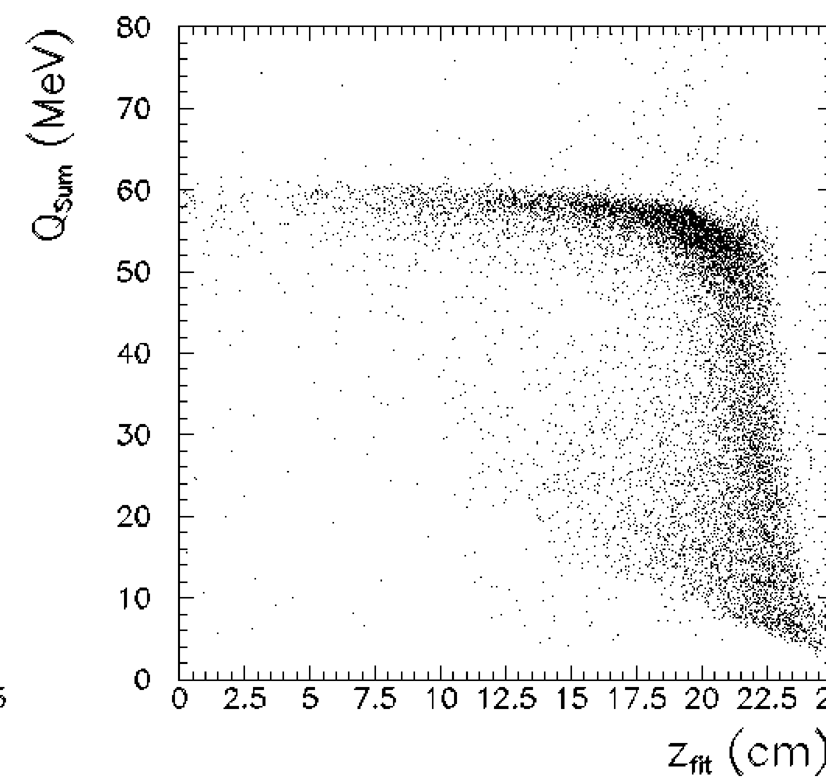


E(linear fit) vs Q(sum) (1/2)

- E(linear fit) and Q(sum) are well correlated
- E(linear fit) “feels” the geometry of the calorimeter, e.g. corrects for the dependence of energy on the conversion point for events closer to the entrance face

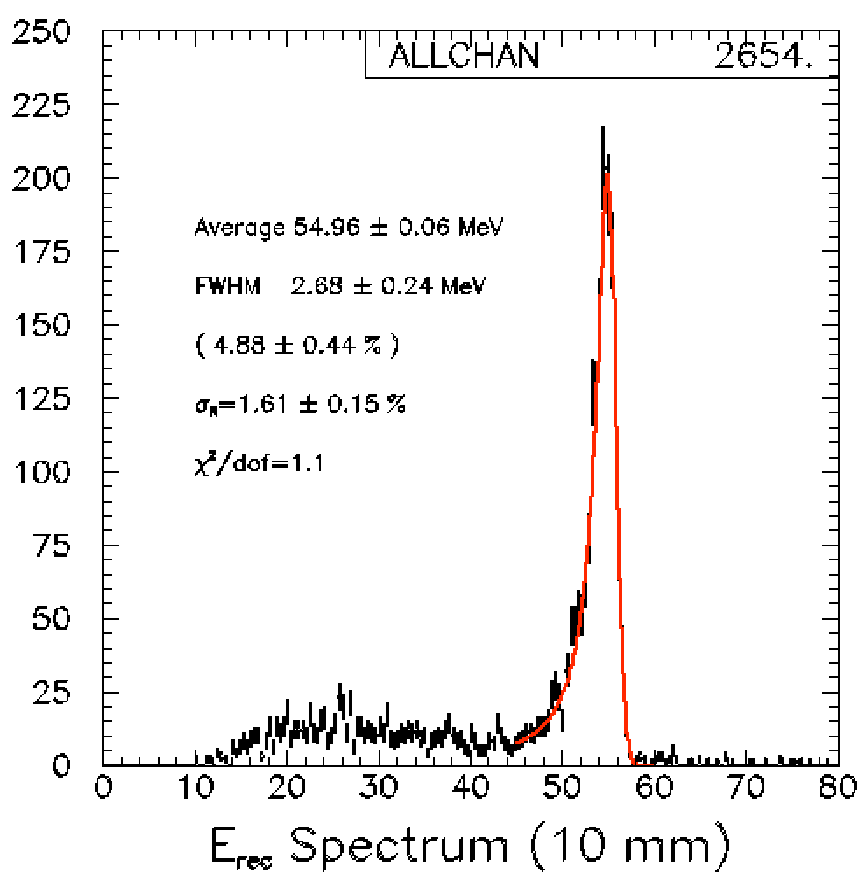


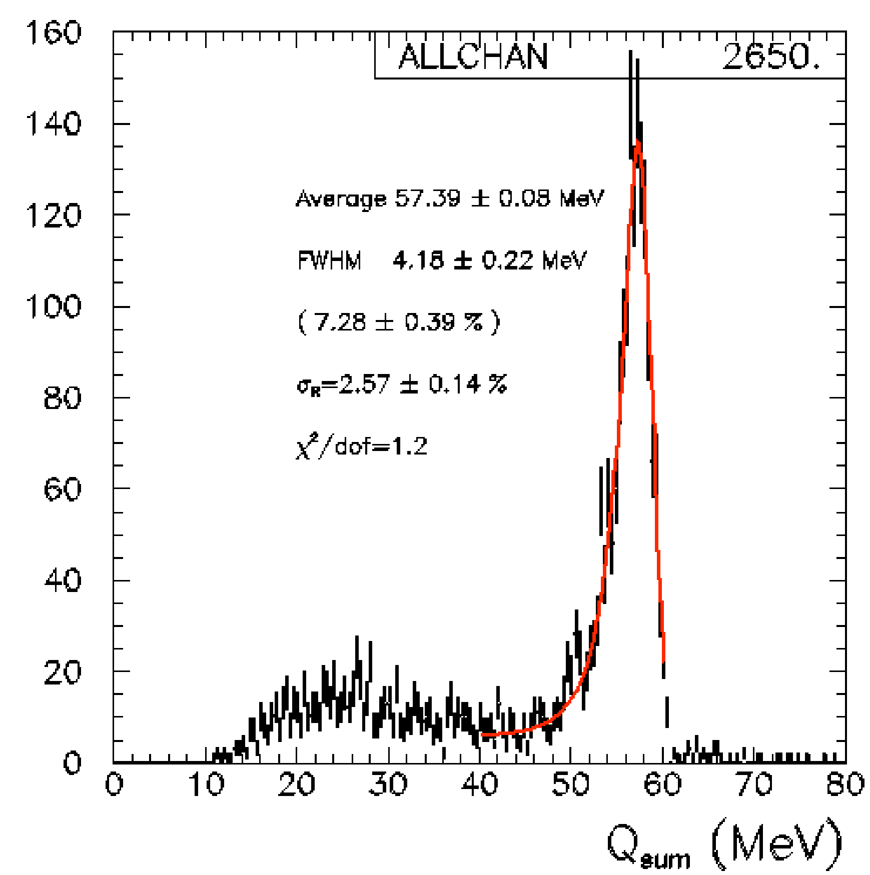




E(linear fit) vs Q(sum) (2/2)

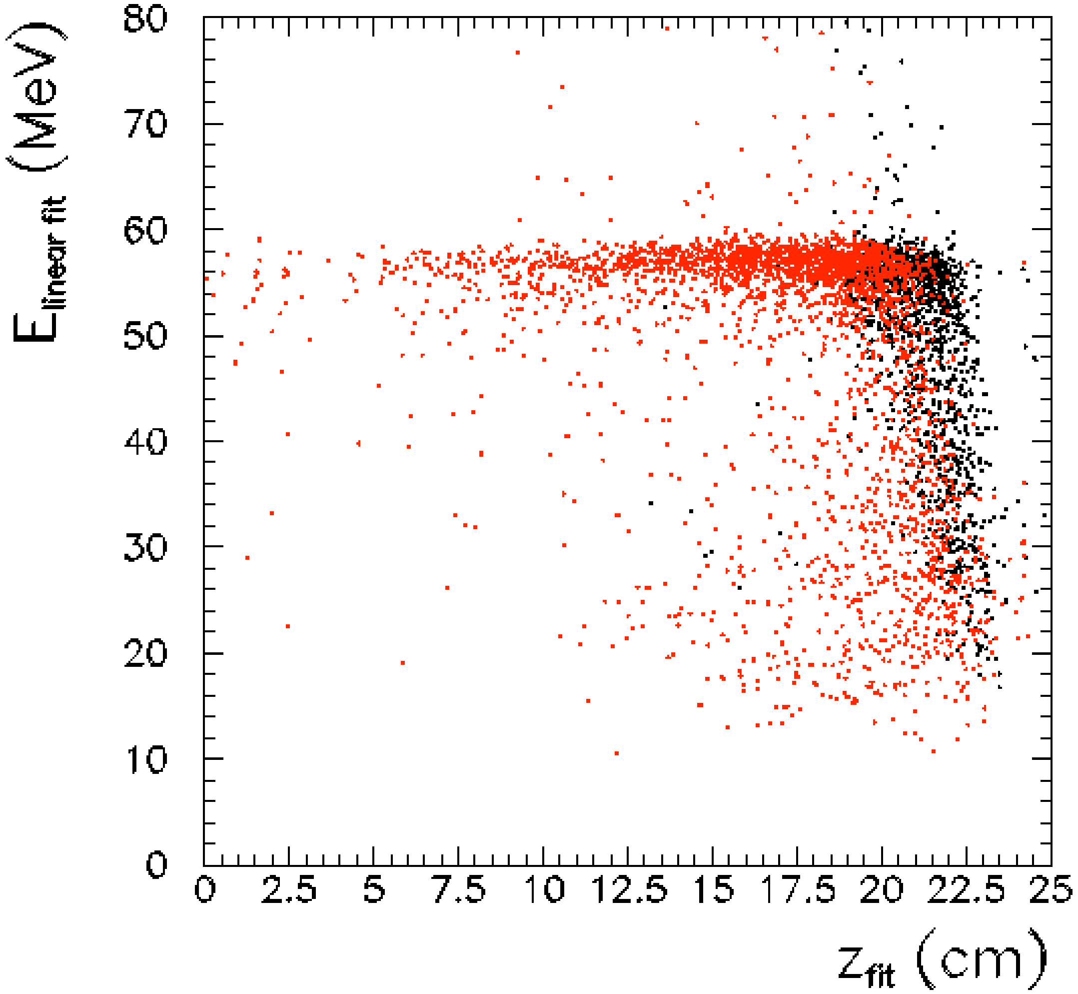
- This results in a sharper peak without the need of hand-made corrections
- Of course it needs a Monte Carlo simulation that reproduces well the reality!

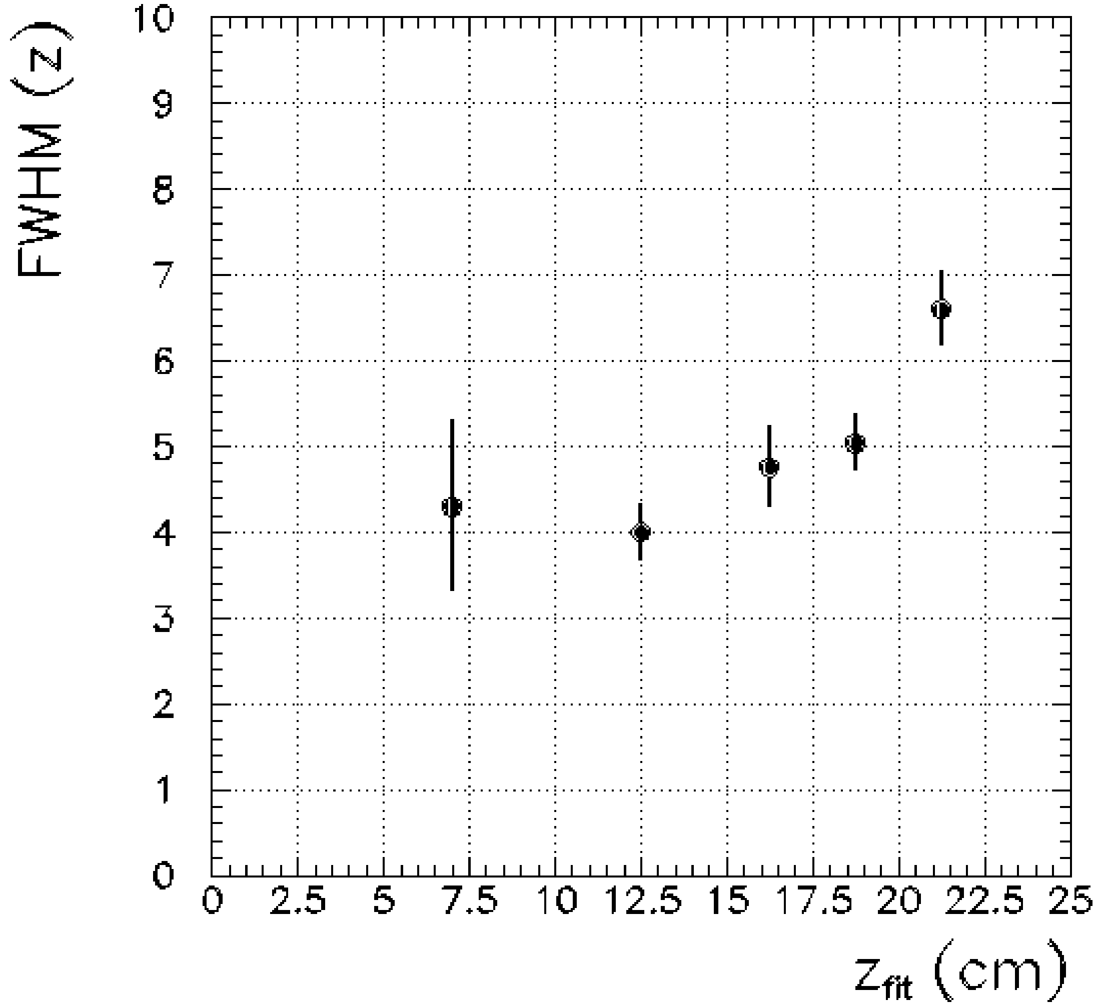




Resolution vs z

- The cut on the saturated PMTs is, essentially, a cut in depth (the resolution is worse because we miss some charge)
  - *5.5%* instead of *4.9%*
- This events could be recovered with a double-range ADC
- Most of high-z events converted before entering LXe





Position resolution